

DEPARTMENT OF COMMERCE

CIRCULAR
OF THE
BUREAU OF STANDARDS
S. W. STRATTON, DIRECTOR

No. 100

NICKEL

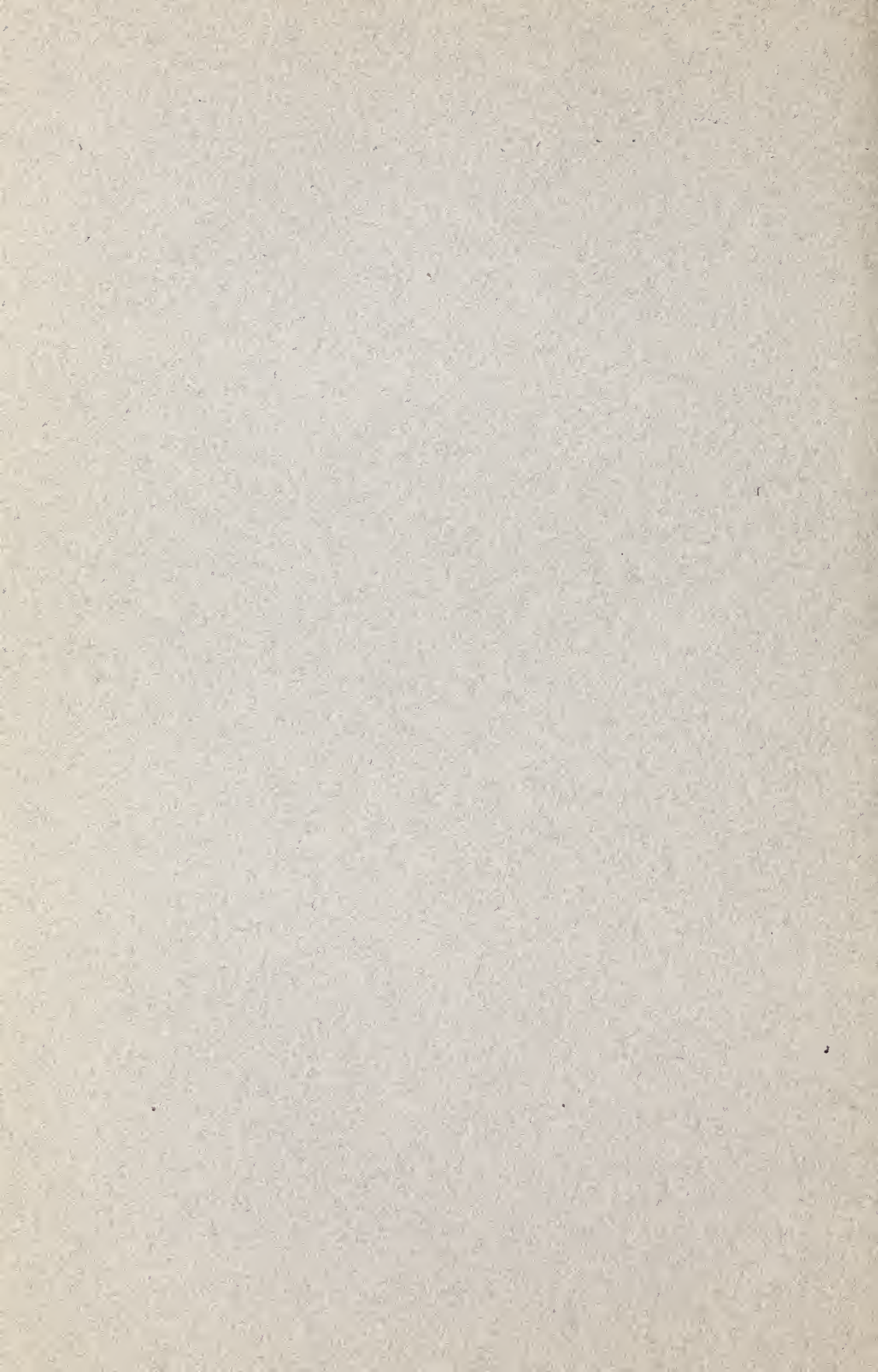
MARCH 21, 1921



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INTRODUCTION

The Bureau is continually in receipt of requests for information concerning the properties, statistics, and manufacture of metals and of alloys, coming from other departments of the Government, technical or purchasing agents of manufacturing firms, or from persons engaged in special investigative work in universities and private technical institutes. Such information is rarely to be found in systematic form; usually the sources of such information are difficult of access, and their accuracy not always certain. Often quoted information of this sort is valueless, either for the reason that the data upon which it is based are actually incorrect or that they have not been properly interpreted.

There are, therefore, being issued from time to time in response to these demands circulars on individual metals or alloys, with the idea of grouping in these circulars all of the best information which the Bureau has as a result of its tests and investigations, together with that available in all records of published tests and investigations of such material.

The circulars deal primarily with the physical properties of the metal or alloy. All other features, except a few statistics of production and such as methods of manufacture, presence of impurities, etc., are discussed only in their relation to these physical properties. It must be realized that the physical properties of metals and alloys are often in great degree dependent upon such factors, so that the statement of values for such properties should include accompanying information regarding these factors by which the properties are affected.

The endeavor, therefore, in the circulars is to reproduce only such data as have passed critical scrutiny and to qualify suitably in the sense outlined above all statements, numerical or otherwise, made relative to the characteristics of the metal. The probable degree of accuracy of data is indicated or implied by the number of significant figures in the values given.

The Bureau has received much valuable assistance and information in the preparation of this circular from The International Nickel Co., the American Brass Co., the Scovill Manufacturing Co., the Driver-Harris Co., the Electrical Alloys Co., the Hoskins Manufacturing Co., and others, for which it wishes to express its grateful appreciation.

PART A. NICKEL

I. SOURCES, METALLURGY, REFINING

The ores from which commercial nickel is obtained are of three classes: (1) *Sulphides*, represented by the pyrrhotite-chalcopyrite ores of Sudbury, Canada, and of Norway, and which contain from 1 to 3 per cent each of copper and nickel, with pentlandite as the nickel carrier; (2) *silicates and oxidized ores*, which are found principally in New Caledonia and contain from 5 to 6 per cent of nickel (plus cobalt), with garnierite as the principal nickel carrier; and (3) *arsenical ores*, which are found in Canada and on the Continent (Saxony) and elsewhere. Of these the first two classes only are of much commercial importance, and the first class furnishes by far the greater proportion of the present output of this metal. In addition to the metal produced from these ores, a small amount of nickel is recovered annually from blister copper.

Sulphide ores are roasted and smelted in the blast furnace to a matte containing approximately 24 per cent of nickel plus copper, 45 per cent of iron, and the balance sulphur. This matte is then blown in a converter to one containing essentially only nickel, copper, and sulphur, which is ready for the refining.

Although the smelting practice of the companies operating with sulphide ore of the Sudbury type is essentially the same, as well as the product (which is usually known as Bessemer matte), the refining of this matte to metal and the separation of the nickel and copper are accomplished by quite widely different processes, of which the following three are the most important:

(1) The Hybinette process, which is in operation in Norway, is essentially an electrolytic one. The matte is roasted to remove the bulk of the sulphur and leached with 10 per cent sulphuric acid, whereby a large proportion of the copper with very little nickel is dissolved out. The residue is melted and cast into anodes, containing about 65 per cent nickel and from 3 to 8 per cent of sulphur, from which, by a combination of electrolysis and cementation of the copper by waste anodes, nickel cathodes and both cement and cathode copper are obtained.

(2) In the Mond process, which is operated in England, the Bessemer matte is first roasted and the copper removed in part by leaching with sulphuric acid with the formation of a solution of copper sulphate. The residue, containing nickel oxide with some copper oxide and iron, is reduced at a low heat to a finely-

divided metallic powder. This is carefully protected from contact with the air, and carbon monoxide is passed over it at from 50 to 80° C. At these temperatures nickel-carbonyl vapor is formed and is decomposed by passing it through a tower containing shot nickel heated to about 200° C; a layer of nickel is formed on the shot, and the carbon monoxide is regenerated and returned to the volatilizing towers. The nickel shot is alternately exposed to and withdrawn from the action of this gas, and in this way a series of concentric layers of nickel are built up around the original nucleus, like the coats of an onion. Mond-nickel shot may readily be distinguished by hammering it upon an anvil, when the various coatings will be broken open, revealing its layer structure.

(3) The Orford process, which is the oldest process for the separation of copper and nickel, is being operated in this country. The Bessemer matte is melted with salt cake, or niter cake, together with coke, in the blast furnace. The sodium sulphide formed by the reduction of the sodium sulphate by the coke, together with the copper sulphide, forms a matte of low specific gravity. The product of the blast furnace is allowed to cool in pots, in which a separation occurs, the upper portion or "tops" containing the greater part of the copper sulphide together with the sodium sulphide, the lower portion or "bottoms" containing the greater part of the nickel sulphide. The "tops" and "bottoms" are readily split apart when cold. Several treatments are required to effect a sufficiently complete separation. The "tops" go to the copper cupola and converter, where they are blown to blister copper. The "bottoms," consisting, essentially, of nickel sulphide or matte, are roasted and leached alternately until they have been completely changed to nickel oxide. This is reduced with charcoal in crucibles or reverberatory furnaces to metallic nickel at a temperature above its melting point, such that the resulting product may be cast into ingots, or blocks, or poured into water to form shot. Electrolytic nickel is also produced by casting this reduced metal at once into anodes and obtaining pure nickel cathodes from them by electrolysis with an electrolyte of nickel sulphate.

The silicate ores of New Caledonia, which contain no sulphur, are first mixed with sulphur-bearing materials, such as gypsum or pyrites, and smelted in the blast furnace to a matte, which is shipped for refining, which in this case, in the absence of copper, consists merely of roasting the nickel matte to oxide and reducing the oxide with charcoal.

TABLE 1.—Composition of Various Grades of Commercial Nickel—Continued

Name	Source	Form	Constituents (percentages)											Remarks
			Cu	Ni and Co	Co	Fe	S	Si	C	Mn	As	Sn and Sb	Insol.	
Nickel cubes.		Cubes	0.10	99.00		0.23	0.008	0.12	0.07					Royal Ontario Nickel Commission.
Do.	Wiggins	do.		99.25										Do.
Grain nickel.	American Nickel Works.	Grain	.13	99.17		.51							1.06	
Mond nickel.	Ludwick Mond.	do.	.014	99.57		.133	.003		.23		Trace	Trace	.03	
Metallic nickel.	Le Nickel.	do.		99.38			.010	.109	.048	0.01				
French nickel.	do.	Rondelle.	.112	99.01		.43	.024		.037				.068	
			.11	99.09	0.32	.65	.04	.01	.04		0.02	0.02		Analyzed by Le Nickel (1905).
Nickel ingots	International Nickel Co.	Ingots	.13	99.10	.80	.50	.06	.10	.10		.015	.015		Analyzed by Orford (1914).
Metallic nickel	Le Nickel.	Brick		99.60			.01	.104	.111					
		Cylinder		99.11			.006	.151	.251					
Nickel rod.	H. Boker & Co.	Rods	.18	97.58		.38	.012	.13	.19	1.60				
Electromalleable nickel.	International Nickel Co.	do.	.10	99.40	.80	.30	.015	.10	.10		Trace	Trace		Analyzed by Orford (1914).
														Typical analyses Orford Works.
Malleable nickel A.	do.	do.		99.00		.55	.025	.10	.15	.15				Do.
														Do.
Malleable nickel B.	do.	do.		98.75		.50	.025	.20	.15	1.75				
Malleable nickel C.	do.	do.		96.75		.75	.03	.20	.15	1.75				
Nickel tube.	H. Boker & Co.	Tube	.75	97.12		.65		.10	.13	1.15				
Nickel castings	International Nickel Co.	Castings		98.95		.50	.035		.16					Do.
Nickel sheet.	Fleitzmann Witte & Co.	Sheet	.12	99.37					.019					
Malleable nickel.	Krupp (Germany).	Sheet No. 1	.12	99.26		.40	.024	.17	.045	Trace				
Do.	do.	Sheet No. 2.	.10	99.05		.40	.045	.16	.13	.13				

II. COMMERCIAL GRADES: USES AND APPLICATIONS

Nickel appears on the market in the following forms:

(a) Grains, cubes, rondelles, or powder reduced at a low temperature from nickel oxide and not fused in the process of manufacture.

(b) Nickel deposited in concentric layers from nickel carbonyl and not fused in the process of manufacture.

(c) Nickel deposited electrolytically in the form of cathode sheets.

(d) Nickel in the form of shot or blocks made by reducing nickel oxide above the melting point of nickel and casting the resulting molten metal or pouring it into water without deoxidation.

(e) Malleable nickel made in the same manner as (d) but treated with some deoxidizer before pouring or teeming into ingots. This nickel appears in the usual commercial forms: rods, sheet, wire, etc.

Most of the commercial production of nickel falls in class (d).

The International Nickel Co. has described certain grades and gives the following average analyses of these materials:

"A" shot nickel, a high carbon nickel used by manufacturers of anodes for nickel plating, containing approximately:

	Per cent		Per cent
Nickel.....	¹ 98.40	Carbon.....	0.50
Iron.....	.60	Silicon.....	.25
Copper.....	.25	Sulphur.....	.06

"X" shot nickel, a purer material used by the manufacturers of crucible nickel steel and of nickel silver, containing approximately:

	Per cent		Per cent
Nickel.....	99.00	Carbon.....	0.18
Iron.....	.45	Silicon.....	.15
Copper.....	.15	Sulphur.....	.035

Ingot or block nickel is almost identical in composition with "X" shot. It is sold in 25 and 50 pound blocks or ingots and is used in the manufacture of open-hearth and electric steel.

Electrolytic nickel in the form of cathodes 24 by 36 inches, weighing about 100 pounds, or in smaller squares for convenience, is used in the manufacture of high-grade nickel silver and cupro-nickel alloys. It contains approximately:

	Per cent		Per cent
Nickel.....	99.80	Carbon.....	0.00
Iron.....	.15	Silicon.....	.00
Copper.....	.05	Sulphur.....	.00

¹ The nickel produced by this company contains about 0.4 per cent cobalt which is included in the figure given for the nickel content.

Malleable nickel, intended for rolling into sheets or rods or for drawing into wire, is made in various grades, according to the purpose for which it is destined. All malleable nickel is treated before casting into ingots with some deoxidizer, generally magnesium, for the purpose of removing the nickel oxide present and making the metal suitable for rolling or forging. Manganese is also added both for the purpose of cleaning the metal and as an alloying element. Nickel can not in general be rolled or forged without this preliminary treatment with a deoxidizer.

The following grades of malleable-nickel ingots are produced for rolling into rods, sheet, and drawing into wire:

Grade "A" malleable nickel:		Grade "C" malleable nickel:	
	Per cent		Per cent
Nickel.....	98.90-99.00	Nickel.....	96.50-97.00
Iron.....	.50	Iron.....	.50-1.00
Manganese.....	.20-.35	Manganese.....	1.50-2.00
Copper.....	.18	Copper.....	.20
Carbon.....	.10	Carbon.....	0.20
Silicon.....	.20	Silicon.....	.15
Sulphur.....	.025	Sulphur.....	.035

Grade "D" malleable nickel is high manganese nickel having practically the same analysis as Grade "C" except that the manganese content is higher, varying from 3 to 6 per cent. This is used principally for spark-plug wire. Wire of this composition resists the action of high temperatures and combustion gases better than the other grades.

Table 1 gives the chemical analyses of a number of samples of commercial nickel, including that of foreign manufacture.

Besides the commercial forms of nickel described above, the metal is on the market in the form of anodes for the metal-plating industry. These cast anodes are quite variable in composition and contain from 88 to 95 per cent of nickel, together with iron, aluminum, tin, silicon, sulphur, and carbon. A typical analysis of a commercial anode is the following:

	Per cent		Per cent
Graphitic carbon.....	1.70	Copper.....	0.15
Silicon.....	.50	Aluminum.....	.03
Iron.....	.80	Nickel.....	96.82

The principal commercial application of nickel is in the manufacture of nickel steel, and this industry absorbed fully 75 per cent of the total nickel production during the war and probably 65 per cent normally. Nickel steels are discussed briefly on page 62.

Besides its use in steel it is used quite extensively as an alloying element with nonferrous metals, principally copper. Many of

these alloys are discussed in more detail below. About 15 per cent of the production is normally utilized in the manufacture of alloys of nickel such as cupronickel and especially nickel silver, the former series of alloys having come into prominence during the war. Nickel coinage and the electroplating industries may each absorb from 2 to 5 per cent of the production, the latter requiring the metal both in the metallic form and in the form of nickel salts; the single salts $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$, and the double salt, $\text{NiSO}_4 \cdot (\text{NH}_4)_2\text{SO}_4 \cdot 6\text{H}_2\text{O}$.

The Bureau has been advised by one of the largest producers of nickel that the nickel of the world, exclusive of that sold as Monel metal, is consumed in the following materials in about the following proportions:

	Per cent		Per cent
Nickel steel.....	65	Malleable nickel.....	5
Nickel anodes.....	5	Miscellaneous.....	10
Nickel silver.....	15		

The production of malleable nickel, although never relatively large compared to that used in the manufacture of steel, has amounted to about 5 per cent of the total production and is steadily growing in volume as the properties of the metal in this form become better known. Malleable nickel is produced in all commercial forms and is used, perhaps, principally for coinage, cooking utensils (chiefly abroad in Germany and Austria), and ornamental and household stampings and fittings. In the form of wire it is much used for motor-ignition spark-plug points, for the suspension wires in electric-light bulbs, for electrical-resistance pyrometers, electrical instruments, and recently in the construction of the audion amplifier.

Some malleable nickel is produced in the form of castings for apparatus—digestions, evaporations, etc.—for the chemical industry, for which its resistance to corrosion in sulphuric and other acids make it peculiarly suitable.

The Edison storage cell contains nickel both in the form of nickel oxide and as nickel anodes. Finely divided nickel is much used as a catalytic agent in the hydrogenation or hardening of oils following the discovery of this property by Sabatier and Senderens (59).² Much information concerning this use of nickel may be found in a recent book by C. Ellis.³ Nickel oxide is used in the ceramic industries for the production of under, or holding, coats of enamel on steel, and also for coloring glazes on pottery.

² These figures relate to the numbered references in the "Bibliography" at the conclusion of this Circular.

³ The Hydrogenation of Oils, Van Nostrand Co., 1919.

Nickel castings have been used with much success as rabble shoes by the International Nickel Co. in calcining furnaces roasting nickel matte. The shoes are exposed to oxidizing and sulphurizing gases at temperatures from 600 to 1000° C and to severe mechanical abrasion; they have stood up in this severe service for nine months, whereas iron shoes would last no more than six or eight weeks.

III. STATISTICS OF PRODUCTION

Tables 2 to 6 show the exports and imports of nickel and nickel products from and into the United States during recent years according to data of the United States Geological Survey (25, 28).

TABLE 2.—Nickel Content of Nickel Salts and Metallic Nickel Produced in the United States as a By-Product in the Electrolytic Refining of Copper, 1911–1919

Year	Quantity	Value	Year	Quantity	Value
	Short tons			Short tons	
1911.....	445	\$127 000	1916.....	918	\$671 192
1912.....	328	93 600	1917.....	402	331 556
1913.....	241	79 393	1918.....	441	401 000
1914.....	423	313 000	1919.....	511	434 485
1915.....	822	538 222			

TABLE 3.—Nickel Imported for Consumption in the United States, 1913–1919

Year	Nickel, nickel ore and matte, nickel alloys of nickel with copper, etc.		Value of manufactured articles of nickel and nickel sheets and strips	Total value
	Quantity	Value		
	Pounds			
1913.....	47 446 520	\$6 562 555	\$38 200	\$6 600 755
1914.....	35 098 958	5 000 594	28 224	5 028 818
1915.....	56 599 381	7 629 686	6 458	7 636 144
1916.....	72 649 377	9 899 340	25 880	9 925 220
1917.....	75 526 767	9 617 163	45 248	9 662 411
1918.....	73 207 147	11 520 775	115 243	11 636 018
1919.....	36 562 388	8 334 135	90 451	8 424 586

TABLE 4.—Nickel Imported for Consumption in the United States, 1916–1919, by Forms

Form	1916		1917	
	Quantity	Value	Quantity	Value
	Pounds		Pounds	
Nickel, alloys, pigs, bars, etc.....	29 917	\$7 869	48	\$19
Ore and matte (nickel content).....	72 611 492	9 889 122	75 510 400	9 612 400
Nickel oxide.....	7 968	2 349	15 926	4 744
Nickel sheets and strips.....		4 896		
Nickel, all other manufactures of.....		20 984		45 248
Total.....	72 649 377	9 925 220	75 526 767	9 662 411

TABLE 4.—Nickel Imported for Consumption in the United States, 1916-1919, by Forms—Continued

Form	1918		1919	
	Quantity	Value	Quantity	Value
	Pounds		Pounds	
Nickel, alloys, pigs, bars, etc	40	\$8	7 258 082	\$2 553 431
Ore and matte (nickel content)	79 193 205	11 517 546	29 303 228	5 780 380
Nickel oxide.....	13 902	3 221	1 078	324
Nickel sheets and strips.....	8 612	6 881	10 152	4 889
Nickel, all other manufactures of.....	10 495	108 362	87 527	85 562
Total.....	73 226 254	11 636 018	36 660 067	8 424 586

TABLE 5.—Imports of Nickel Ore and Matte into the United States in 1917 and 1918, by Countries

Country	1917			1918				
	Nickel ore and matte			Nickel ore and matte			Manufactures	
	Quantity	Nickel content	Value	Quantity	Nickel content	Value	Quantity	Value
	Short tons	Pounds		Short tons	Pounds		Pounds	
Canada.....	65 916	73 530 259	\$9 138 994	63 835	70 645 034	\$10 974 325	9 518	\$4 441
Australia.....	2 463	1 980 534	473 406	2 339	2 027 850	433 878	.....	.....
Other British Oceania.....	.....	.....	.....	489	409 023	85 934	.....	.....
Chile.....	.....	.....	.....	1	91	44	.....	.....
French Oceania.....	.....	.....	.....	112	111 207	23 365	.....	.....
France.....	.....	.....	.....	.....	.....	.....	86	411
Switzerland.....	.....	.....	.....	.....	.....	.....	1 172	12 339
England.....	.....	.....	.....	.....	.....	.....	9 328	5 517
Japan.....	.....	.....	.....	.....	.....	.....	4 870	6 671
Total.....	68 379	75 510 793	9 612 400	66 776	73 193 205	11 517 546	24 974	29 379

TABLE 6.—Nickel, Nickel Oxide, and Matte ^a Exported from the United States, 1909-1918

Year	Quantity	Value	Year	Quantity	Value
	Pounds			Pounds	
1909.....	12 048 737	\$4 101 976	1914.....	27 595 152	\$9 455 528
1910.....	15 244 937	4 704 088	1915.....	26 418 550	10 128 514
1911.....	25 099 586	8 283 777	1916.....	33 404 011	12 952 493
1912.....	25 815 016	8 515 332	1917.....	21 992 820	8 936 620
1913.....	29 173 088	9 686 794	1918.....	17 469 500	6 927 041

^a No nickel matte is known to have been exported in the years 1911 to 1918, inclusive.

IV. METALLOGRAPHY

As far as is known, nickel exists in only one solid modification or phase which is stable at all temperatures up to that of its melting point. It suffers, however, a magnetic transformation, in a

manner quite similar to iron, at about 360°C . Below this temperature it is ferromagnetic, above it is only weakly paramagnetic. Values of the temperature of this transformation varying from 320 to 370°C have been obtained by different investigators working with nickel of different degrees of purity and are shown in Table 7. There is, therefore, some uncertainty attaching to the exact temperature of this transformation, and the value accepted above represents the results of those who worked with the purest material. The magnetic transformation of nickel, as in the case of iron, is accompanied as well by changes in the other physical properties, such as density, resistivity, and thermoelectromotive force or in their temperature derivatives.

According to Hull (35) the atoms are arranged in a nickel crystal in the face-centered-cube formation, giving rise to the regular crystalline form of this metal.

As the magnetic transformation of nickel is not accompanied by any determinable alteration in structure or recrystallization, the microstructure of this material is relatively simple, at least when compared with that of iron and steel. The impurities which are invariably found in commercial nickel are with three exceptions soluble in the solid state in the amounts in which they are usually present; namely, iron, copper, manganese, cobalt, and silicon. Nickel oxide, sulphides (of nickel or manganese), and carbon are at times visible as separate constituents in nickel. In addition there may be found in all malleable nickel a small amount of compounds (oxides) of magnesium in the form of small round particles.

TABLE 7.—Temperature of the Magnetic Transformation of Nickel

Reference	Chemical composition					Temperature of transformation
	Cu	Fe	Co	Si	C	
	Per cent (a)	Per cent (a)	Per cent (a)	Per cent (a)		$^{\circ}\text{C}$
Copaux (82).....						340
Guertler and Tammann (337)	Trace	0.47	1.86			320-325
Curie.....						340
	0.20	Trace	.15	0		345
	.80	Trace	Trace	.20		340
Pechoux (115).....	.40	.60	.10	.15		345
	Trace	1.50	.50	.10		335
Jänecke (38).....						347-356
Werner (40).....						352-355
Stark-Tataczenko (42).....						370
Baikow (44).....						360

^a Cobalt-free nickel melted under hydrogen.

Fig. 1 shows the structure of commercial nickel blocks and the appearance of the nickel, nickel-oxide eutectic, which is found of course only in nonmalleable nickel, as it is impossible to work the metal containing it at any temperature. The structure of malleable nickel in the form of hot-rolled rod is shown in Fig. 2; only the grains of nickel and the small particles of magnesium (and possibly manganese) oxides are visible. Carbon is soluble in nickel to the extent usually of 0.40 per cent, and is, therefore, not ordinarily found in any other form in commercial nickel. Above that percentage, however, it begins to separate out in the form of graphite; Fig. 3 shows the appearance of graphite in rolled nickel.

Nickel is subject to a peculiar type of intercrystalline brittleness which has been well described structurally by Rawdon and Krynitzky (37). When exposed at high temperatures—that is, from 1000 to 1200° C—to the action of oxidizing or sulphurizing gases the boundaries of the grains at the surface are attacked, either oxidized or sulphurized, and the cohesion between the grains destroyed. These surface layers become quite brittle and will not elongate or flow under subsequent drawing or rolling operations, but there is produced a network of fine cracks on the surface under such treatment. The presence of these cracks indicates a faulty heating operation; that is, either the flame was too oxidizing and “burnt” the metal or it introduced sulphur into it. Fig. 4 shows the structure of such “heat-checked” nickel sheet.

Nickel is best etched for metallographic examination with nitric acid, and for that purpose a volume concentration from 75 to 100 per cent acid may be used. Somewhat better results may be obtained by using a solution of nitric acid of a volume concentration of from 50 to 75 per cent, made up by diluting the concentrated acid with a solution containing 50 per cent glacial acetic acid in water; these acetic acid solutions appear to give more uniform results than the aqueous solution, in which the metal is readily inclined to assume the passive state.

Electrolytic etching is also recommended for nickel, an electrolyte of sulphuric acid and hydrogen peroxide being used:

	Per cent
Sulphuric acid.	22
Hydrogen-peroxide solution.	12
Water.	66

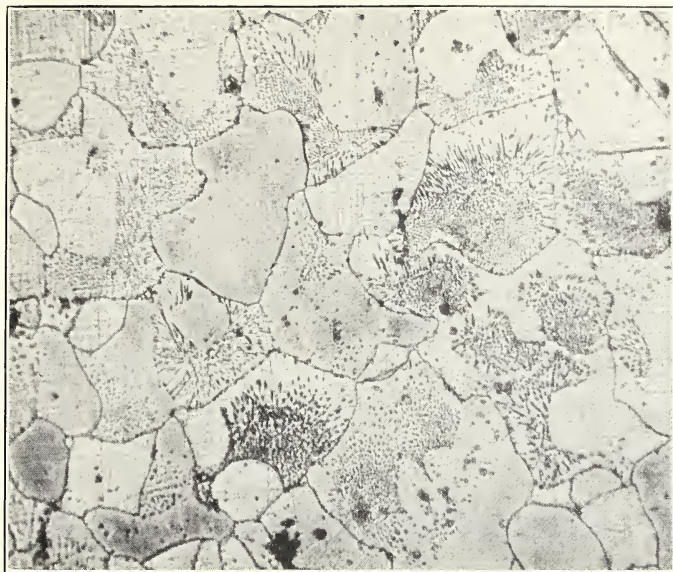


FIG. 1.—Microstructure of nickel blocks showing nickel, nickel-oxide eutectic. $\times 100$

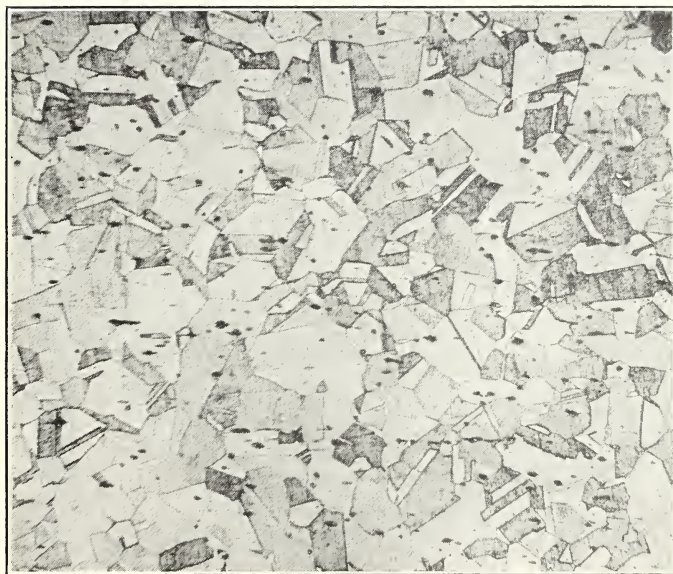


FIG. 2.—Microstructure of hot-rolled nickel rod showing oxides inclusions. $\times 100$



FIG. 3.—Microstructure of rolled nickel rod containing precipitated graphite in the form of fine particles. $\times 100$



FIG. 4.—Microstructure of cross section of heat-checked nickel sheet, showing intercrystalline oxidation of surface layers. $\times 100$

V. CHEMICAL PROPERTIES

Nickel is not an active element chemically. It is not attacked at ordinary temperatures by air, by fresh or sea water, or combinations of the two. Organic acids such as acetic, oxalic, tartaric, and citric acids attack it appreciably only after long periods of contact. Sulphuric and hydrochloric acids dissolve it slowly only; in nitric acid on the other hand it is very readily dissolved. Alkalis either in the fused state or in solution in water are without effect upon it, and for this reason, laboratory fusions with these substances are carried out in crucibles of this metal. At temperatures around 500°C it becomes slightly oxidized in the air and also decomposes water with formation of hydrogen.

Hale and Foster (64) have measured the rate of solution of nickel sheet in various solutions at ordinary temperature, and their results expressed in loss of weight per 100 cm^2 are given in Table 8.

TABLE 8.—Corrosion Tests of Nickel

Specimens immersed in—	Loss of weight in 7 days (solution renewed daily)	Loss of weight in 28 days (solution not renewed)
	grams	grams
HNO_3 (N/5).....	4.2	2.1
HCl (N/5).....	.25	.45
H_2SO_4 (N/5).....	.25	.40
MgCl_2 (N/5).....	.05	.10
NaOH (N/5).....	.00	.00
CaCl_2 (N/5).....	.08	.05
NaCl (N/5).....	.00	.00
NH_4OH (N/5).....	.00	.00
Na_2CO_3 (N/5).....	.00	.00

The use of nickel for cooking utensils which is quite extensive in Germany has inspired numerous investigators to study the question of the solution of the nickel by the liquids used and its absorption by the food, as well as the physiological effect of the amounts thus absorbed (65–70). The results of these investigations have usually been expressed in terms of milligrams of nickel found in 100 g of the food and varied from 0.01 mg to a maximum of 64 mg, the high results being obtained by the use of salt and vinegar, or food containing both. Vuk (65) found losses of from 15 to 65 mg of nickel per square meter of exposed surface after boiling in 5 per cent acetic acid for two and one-half hours. These

small amounts of nickel thus absorbed by food from nickel utensils have been regarded as being entirely harmless physiologically.

The heats of formation of some of the more important compounds of nickel are given by Richards (19).

NiO.....	grams 74.5	Cal./gram 61 500
NiS.....	90.5	19 500

Sieverts (56) has determined the solubility of hydrogen in nickel and finds that it forms with nickel a homogeneous solid solution. The solubility of hydrogen both in solid and in molten nickel is proportional to the square root of the hydrogen pressure. He found that 100 g of nickel absorb

0.16 mg of hydrogen at 760 mm pressure, 212° C

.39 mg of hydrogen at 760 mm pressure, 520° C

.98 mg of hydrogen at 760 mm pressure, 1023° C

1.50 mg of hydrogen at 760 mm pressure, 1400° C

and that this amount liberates 1.9 mg of hydrogen upon solidification at 1452° C in a hydrogen atmosphere of 760 mm pressure.

VI. PHYSICAL PROPERTIES

1. DENSITY

The density and specific gravity of nickel varies greatly according to its chemical composition, physical condition, and the mechanical treatment which it has received. Metal which has been reduced by carbon, or carbon monoxide, to a powder or sponge, contains numerous voids and may have a density as low as from 7.7 to 8.0, values which have been obtained for powder and rondelles, or grain nickel.

Dense nickel, such as electro, or malleable nickel will vary in density from 8.70 to 8.90, averaging about 8.84, which may be taken as quite closely representing the bulk of commercial material. This corresponds to 552 pounds per cubic foot, or 0.319 pound per cubic inch.

2. CHANGE OF STATE

The melting point of nickel is given by the Bureau of Standards (84) as 1452° C. The element undergoes a magnetic transformation, accompanied possibly by a phase change at from 340 to 360° C (Copaux, 82; Pecheux, 115). The transformation point in commercial nickel, containing impurities is lower, usually in the region of 320° C (Guertler and Tammann, 337; Pecheux 115).

The boiling point of nickel has never been determined.

The heat of transformation is 1.33 cal./gram according to Wüst (90), and the heat of fusion, 56.1 cal./gram. Dr. W. P. White has recently determined the latent heat of fusion of nickel at 1450° C as 74 cal./gram.

3. SPECIFIC HEAT OF NICKEL (WÜST)

Wüst has recently (90) determined the specific heat of nickel (analysis not given) from 0 to 1520° C (results given in Table 9).

TABLE 9.—Specific Heat of Nickel

Temperature	Mean specific heat	True specific heat	Temperature	Mean specific heat	True specific heat
	$\frac{q_t - q_0}{t}$	$\frac{dq}{dt}$		$\frac{q_t - q_0}{t}$	$\frac{dq}{dt}$
° C	cal./gram/°C	cal./gram/°C	° C	cal./gram/°C	cal./gram/°C
0.....		0.1095	900.....	0.1299	0.1295
100.....	0.1147	.1200	1000.....	.1298	.1295
200.....	.1200	.1305	1100.....	.1298	.1296
300.....	.1252	.1409	1200.....	.1298	.1296
320.....	.1263	.1430	1300.....	.1298	.1296
330.....	.1306	.1294	1400.....	.1298	.1296
400.....	.1304	.1294	1451.....	.1298	.1296
500.....	.1302	.1294	1451.....	.1684	.1338
600.....	.1301	.1294	1500.....	.1673	.1338
700.....	.1300	.1295	1520.....	.1668	.1338
800.....	.1299	.1295			

Jaeger and Dieselhorst (121) determined the true specific heat at 18 and at 100° C of a sample of nickel containing:

	Per cent		Per cent
Co.....	1.36	Si.....	0.06
Cu.....	.15	Mn.....	1.04
Fe.....	.44		

They find the following values:

$$\sigma_{18^\circ\text{C}} = 0.1065 \text{ cal./gram/}^\circ\text{C, and } \sigma_{100^\circ\text{C}} = 0.1160 \text{ cal./gram/}^\circ\text{C}$$

Schimpff (93) finds the following values of the mean specific heat of nickel containing 1.5 per cent Co, 0.6 per cent Fe, and 97.9 per cent Ni:

$$\sigma_m (17 \text{ to } 100^\circ\text{C}) = 0.1084 \text{ cal./gram/}^\circ\text{C}$$

$$\sigma_m (17 \text{ to } 79^\circ\text{C}) = .0973 \text{ cal./gram/}^\circ\text{C}$$

$$\sigma_m (17 \text{ to } 190^\circ\text{C}) = .0830 \text{ cal./gram/}^\circ\text{C}$$

4. THERMAL EXPANSIVITY

Guillaume (107) gives the equation for the thermal expansivity between 0 and 40° C of five bars of commercial nickel:

$$\frac{\Delta l}{l_0 t} = (a + bt) 10^{-5}$$

in which coefficients a and b had the following values:

	a	b		a	b
1.....	12.66	0.0055	4.....	12.49	0.0073
2.....	12.52	.0066	5.....	12.55	.0054
3.....	12.49	.0070			

Tutton (105) finds the following values of a and b for the same equation, between 6 and 121° C: $a = 12.48$, $b = 0.0074$.

Between 0 and 300° C Harrison (103) finds that the expansivity of "pure nickel" can be represented by the following equation:

$$\frac{\Delta l}{l_0 t} = (12.80 + 0.0075 t + 0.000035 t^2) 10^{-5}$$

Above 375° C Holborn and Day (104) give the following equation for the expansivity, as calculated from their measurement on a nickel of which no analysis is given:

$$\frac{\Delta l}{l_0 t} = (13.46 + 0.0033 t) 10^{-5}$$

Material	Average coefficients ^a of expansion $\times 10^6$.		
	Room temperature to 100° C	Room temperature to 300° C	300 to 600° C
10 samples of commercial nickel (94 to 99 per cent nickel).....	12.9 to 13.5	13.8 to 14.6	15.3 to 17.0
10 samples of monel metal (60 to 68 per cent nickel).....	14.5 to 15.1	14.9 to 15.1	15.9 to 18.4

^a As recently determined by Souder and Hidaert at the Bureau of Standards.

5. THERMAL CONDUCTIVITY

The best determinations of the thermal conductivity of nickel are those of Lees (110) and of Jaeger and Dieselhorst (121):

$$\begin{array}{l} \text{Lees—Electrolytic nickel, no analysis.....} \left\{ \begin{array}{l} \lambda_0 = 0.140 \text{ cal./gram/second/}^\circ \text{C} \\ \lambda_{18^\circ \text{C}} = .140 \text{ cal./gram/second/}^\circ \text{C} \end{array} \right. \\ \text{Jaeger and Dieselhorst—1.36 Co, 0.44 Fe, 1.04 Mn} \left\{ \begin{array}{l} \lambda_{133^\circ \text{C}} = .142 \text{ cal./gram/second/}^\circ \text{C} \\ .15 \text{ Cu, .06 Si.....} \left\{ \begin{array}{l} \lambda_{100^\circ \text{C}} = .138 \text{ cal./gram/second/}^\circ \text{C} \end{array} \right. \end{array} \right. \end{array}$$

Fig. 5 gives results by Lees and by Angell (109) on the thermal conductivity at higher and lower temperatures.

6. ELECTRICAL RESISTIVITY

A number of precise determinations of the electric resistivity of nickel have been made, but the nickel used was in many cases

quite impure and the values of the resistivity so obtained are much higher than the value for pure nickel. The following table gives several of the values which have been observed:

TABLE 10.—Electrical Resistivity of Nickel

Reference	Material	Electrical resistivity at 0° C	Temperature coefficient 0 to 100° C
		microhms-cm	
Fleming (120).....	Electrolytic, no analysis given.....	6.926	0.0061
Copaux (82).....	Pure, reduced from oxalate, no analysis....	6.4	.0066
Campbell (119).....	Purchased in Germany in 1901.....	8	.....
Pechoux (115).....	0.20 Cu, 0.15 Co, No C or Si, trace Fe, 0.35 total impurities	9	.0058
Ruer and Kaneko (298).....	Kahlbaum, 0.035 C.....	7.7	.....
Jaeger and Dieselhorst (121)...	1.36 Co, 0.44 Fe, 1.04 Mn, 0.15 Cu, 0.06 Si.	^a 11.76	.0044

^a At 18° C.

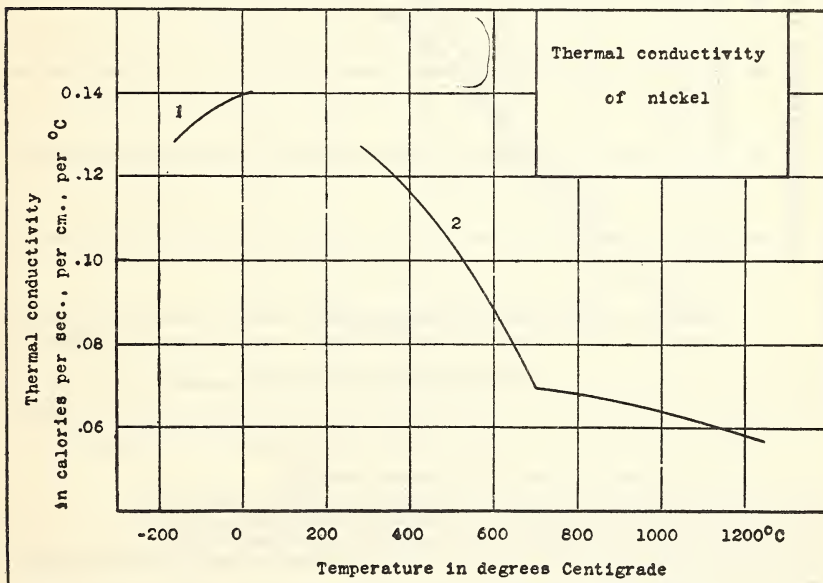


FIG. 5.—The thermal conductivity of nickel at higher and lower temperatures

Curve 1, from determinations of Lees (110) on 99 per cent nickel bar

Curve 2, from determinations of Angell (109) on nickel rod from Boker, no analysis given

The most probable value for the resistivity of pure nickel from the above determinations is the lowest, that of Copaux; with this lowest value is associated also the highest temperature coefficient. The other values are higher, due to the presence of impurities which depress also the value of the temperature coefficient. The

most probable value of the latter between 0 and 100° C is that given by Copaux; that is, 0.0066.

Fig. 6 gives the results of several determinations of the electrical resistivity at higher and lower temperatures, and Fig. 7 the results of one series of determinations of the influence of temperature on the temperature coefficient of resistivity by Somerville (116). At the transformation point the resistivity-temperature curve changes

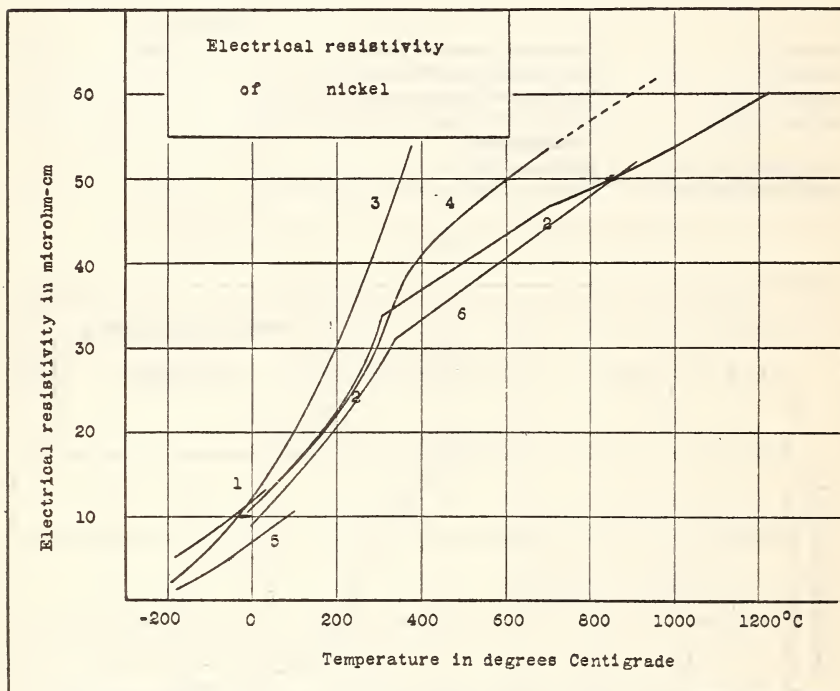


FIG. 6.—The electrical resistivity of nickel at higher and lower temperatures

Curve 1, from determinations of Lees (110) on 99 per cent nickel bar

Curve 2, from determinations of Angell (109) on nickel rod from Boker, no analysis given

Curve 3, from determinations of Niccolai (117) on Kahlbaum nickel, analysis not given

Curve 4, from determinations of Harrison (118) on nickel wire, not otherwise described

Curve 5, from determinations of Fleming (120) on electrolytic nickel, annealed in hydrogen and drawn into wire, no analysis given

Curve 6, from determinations of Pecheux (115) on nickel of the following composition:

Cu.....	0.20 per cent
Fe.....	Trace
Co.....	0.15 per cent
C+Si.....	None

Total impurities=0.35

its slope and there is a marked change in the value of the temperature coefficient.

The Driver-Harris Co. reports its 99 per cent nickel (grade A above) wire as having a resistivity of 64.3 ohms-mil-foot (10.68

microhm-cm) at 24° C, with a temperature coefficient, $\alpha_{24^\circ\text{C}}$, of 0.0041. The other grades of malleable nickel of higher manganese content have higher values of resistivity and its temperature coefficient, thus:

Grade D nickel (4.5 per cent of manganese) has a resistivity of 20 microhm-cm with a temperature coefficient of 0.0020.

7. THERMOELECTROMOTIVE FORCE

Fig. 8 gives the results of determinations of the thermoelectromotive force of nickel to platinum, lead, copper, and silver.

8. MAGNETIC PROPERTIES

Nickel is ferromagnetic at ordinary temperatures and up to the temperature of its magnetic transformation, at 340 to 360° C.

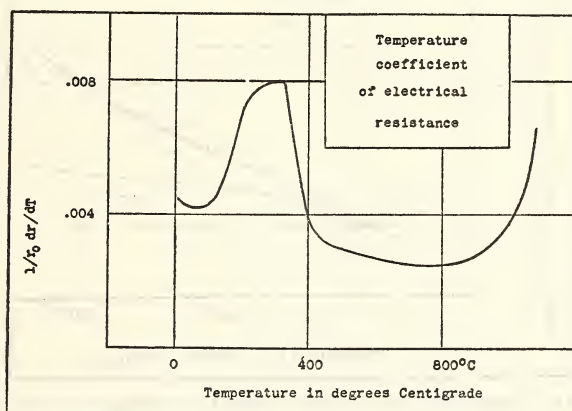


FIG. 7.—The temperature coefficient of electrical resistance of nickel according to Somerville (116)

The coefficient measured is:

$$\frac{1}{r_0} \frac{dr}{dt} \text{ when } r_0 = \text{the resistivity at } 0^\circ \text{C}$$

Above this temperature it is paramagnetic and follows Curie's law (132). Fig. 9 gives the results of some magnetic tests of nickel.

The susceptibility of nickel in any direction is markedly diminished by the application of a tensile stress and augmented by that of compressive stress in that direction (140, 141).

The permeability of nickel increases with temperature up to 300 to 340° C (Ewing, 143, 145).

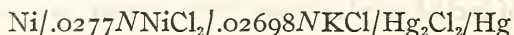
9. ELECTROLYTIC-SOLUTION POTENTIAL; PASSIVITY

The true reversible potential of nickel in a normal aqueous nickel-sulphate solution is given by Schoch (152) as -0.48 , measured against the normal calomel electrode. Schoch attributes

the higher values obtained by other investigators to occluded hydrogen.

Schweitzer (151) gives the value -0.612 volt for the potential of nickel powder in contact with N NiSO_4 and -0.596 volt for nickel powder in contact with $N/1$ NiCl_2 . Both were measured against the normal calomel electrode.

Measurement has been made by N. Isgarischew (154) of the potential of nickel against a solution of NiCl_2 in methyl alcohol. The combination was:



At a temperature of 25°C the potential difference was 0.247 volt.

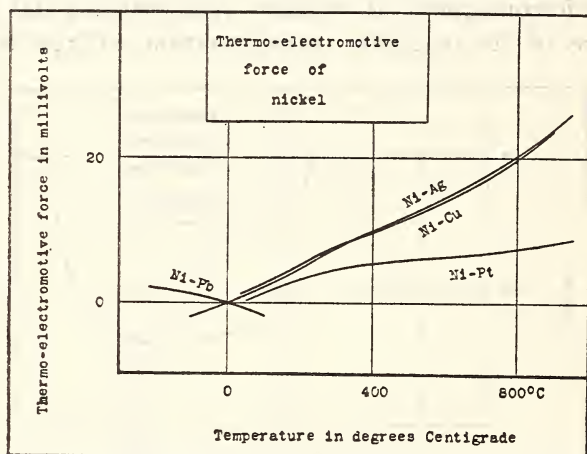


FIG. 8.—The thermo-electromotive force of nickel to platinum, copper, and silver

Ni-Ag, according to determinations of Hevesy and Wolff (125) on nickel wire, no analysis given, furnished by the Vereinigte deutsche Nickel Werke

Ni-Pt, calculated from the preceding results on the *Ni-Ag* couple, together with those of Holborn and Day on the *Ag-Pt* couple

Ni-Cu, according to determinations of Pecheux (126) on nickel wire of the following compositions: Cu, 0.20; Co, 0.15; Fe, trace; C+Si, none; total impurities, 0.35

Ni-Pb, according to determinations of Dewar and Fleming (128) on Mond nickel

The electromotive force developed is such that the current flows at the 0°C junction from the Ag, the Cu, or the Pt to the Ni, when the EMF is +

Nickel becomes passive (157); that is, it behaves like a noble metal to a greater degree than do other metals of high solution potential. This state may be established by simple immersion in strong oxidizing agents like nitric acid or bichromate solutions. The condition of passivity may often be destroyed by slight changes in the chemical environment or by scratching or mechanical shock. Pure nickel as an anode is readily rendered passive in electrolytes containing salts of oxygen acids, especially at high

current densities. The presence of impurities in the anodes as well as of chlorides or fluorides in the electrolyte tends to prevent passivity. Coincident with the establishment of passivity there is pronounced drop in the solution potential.

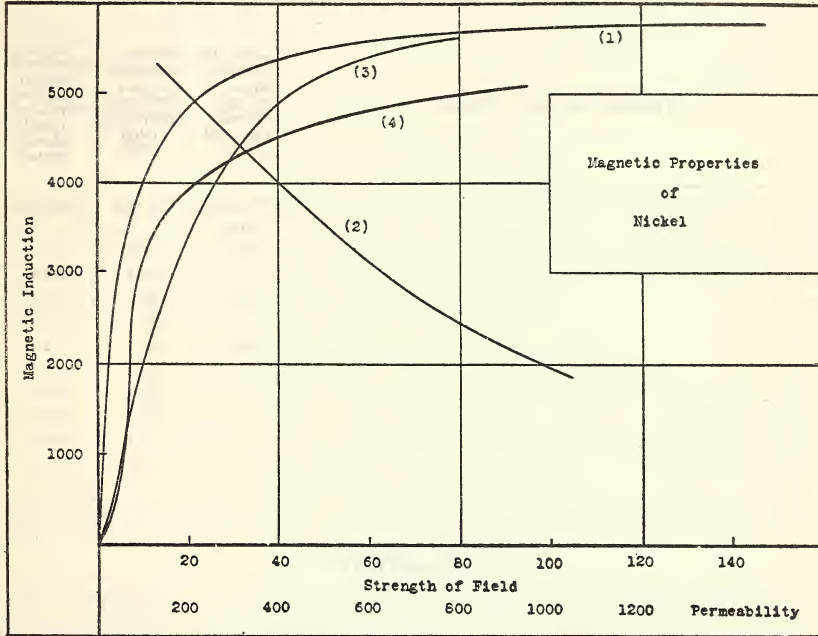


FIG. 9.—The magnetic properties of nickel

Curve 1, induction curve for malleable nickel (International Nickel Co) containing: Ni, 98.82 per cent; Fe, 0.46 per cent; C, 0.11 per cent; S, 0.22 per cent; Cu, 0.18 per cent; Mn, 0.27 per cent; Si, 0.13 per cent. (Burrows method)

Curve 2, permeability curve for same material

Curve 3, induction curve of nickel, composition unknown. Perkins (146)

Curve 4, induction curve of nickel, composition unknown. Ewing (145)

10. OPTICAL PROPERTIES

One of the commercially most important properties of nickel is its ability of taking and retaining a high polish and of reflecting a large percentage of light incident on such a polished surface. This is, for example, one of the properties which make the metal valuable for electroplating. In Table 11 are given the best values of the reflectivity of both nickel and Monel metal; those of the Bureau of Standards are recent (1920)⁴ and were obtained on samples of typical commercial rolled materials.

⁴ W. W. Coblenz, Reflecting power of Monel metal, stellite, and zinc, B. S. Sci. Papers, No. 379.

Meyer (170) gives the following values for the optical constants of nickel:

Reflectivity = 65.5 per cent for $\lambda = 0.589\mu$
 Absorption index (K) = 3.42 per cent for $\lambda = .589\mu$
 Refractive index (n) = 1.58 per cent for $\lambda = .589\mu$

TABLE 11.—Optical Reflectivity of Nickel and Monel Metal

Wave length of light in microns	Hagen and Rubens values on electrolytically deposited nickel	Bureau of Standards values (1920) on commercial rolled nickel	Bureau of Standards values (1920) on commercial rolled Monel metal
	Per cent	Per cent	Per cent
0.42.....	56.6		
.50.....	60.8	61.5	57.7
.55.....		63.2	59.0
.60.....	64.9	64.0	60.1
.65.....		65.1	61.6
.70.....	68.8	67.1	62.8
.75.....		68.5	64.5
.80.....		67.2	^a 67.2
1.00.....		72.5	^a 72.5
2.00.....		83.8	^a 83.8
3.00.....		88.7	^a 88.7
4.00.....		91.0	^a 91.0

^a Infra-red.

11. ELASTICITY

According to determinations of Harrison (177), Grüneisen (179), Schaefer (189), Searle (191), and Guillaüme (107), the value of Young's modulus for nickel varies from 21 000 to 23 000 kg/mm² (30 000 000 to 33 000 000 lb./in.²)

Koch and Dannecker (176) and Harrison (177) have determined the values of the modulus of torsional elasticity and of Young's modulus, respectively, at higher temperatures; their values are given in Table 12.

TABLE 12.—Modulus of Elasticity of Nickel

Temperature in degrees centigrade	Modulus of elasticity in torsion	Young's modulus	Temperature in degrees centigrade	Modulus of elasticity in torsion	Young's modulus
	kg/mm ²	kg/mm ²		kg/mm ²	kg/mm ²
20.....		22 000	400.....	7120	
27.5.....	7300		401.....		15 700
96.....		21 300	465.....		11 900
110.....	6430		600.....	6080	
200.....	6860		800.....	4940	
222.....		20 300	1000.....	3730	
300.....	7390		1200.....	2900	
329.....		17 800	1300.....	2480	

Poisson's ratio for nickel is 0.33 according to Benton (190).

12. HARDNESS

In the annealed condition the scleroscope hardness of nickel of low carbon (0.10 per cent) and manganese (0.30) content will vary from 9 to 12 (universal hammer). The Brinell hardness (3000 kg) of the same material varies from 80 to 100. The effect of carbon and manganese on the hardness of annealed metal is discussed below. When hardened by cold working the scleroscope hardness may be raised to 40 to 45, the Brinell hardness, to 250 to 350.

13. TENSILE PROPERTIES

Table 13 gives the values usually obtained for the tensile properties of nickel of low carbon and manganese content in various conditions. (These values refer to malleable A-nickel of the International Nickel Co.; for compositions, see p. 7).

TABLE 13.—Tensile Properties of Nickel

Kind of nickel	Tensile strength	Yield point	Elonga- tion in 2 inches	Reduc- tion in area
	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
Rolled and annealed malleable nickel.....	65 000 to 75 000	20 000 to 25 000	40-50	40-60
Hot-rolled rods.....	68 000 to 78 000	21 000 to 26 000	40-50	40-60
Sheet... {	Hard-rolled.....	120 000 to 130 000	110 000 to 120 000	5-10
	Annealed.....	65 000 to 75 000	20 000 to 25 000	40-50
Wire... {	Hard-drawn.....	120 000 to 160 000	.....	.....
	Annealed.....	65 000 to 750 000	.....	.....
Cast nickel (deoxidized).....	55 000	20 000	25	.....

Table 14 gives the results of tests by Bregowsky and Spring (195) of the tensile properties of nickel at higher temperatures.

TABLE 14.—Tensile Properties at Higher Temperatures According to Bregowsky and Spring (195) of Cast Nickel of Unknown Purity

Temperature in degrees centigrade	Tensile strength		Yield point	Temperature in degrees centigrade	Tensile strength		Yield point
	Lbs./in. ²	Lbs./in. ²			Lbs./in. ²	Lbs./in. ²	
21.....	38 000	23 800	460.....	.....	28 500	.....	.....
149.....	40 900	25 100	482.....	.....	27 800	14 200	.....
232.....	36 700	25 100	499.....	.....	31 900	.....	.....
315.....	35 900	22 900	538.....	.....	16 800	.....	.....
399.....	36 600	22 600	.....	.....	.....	.....	.....

Mr. W. P. Sykes,⁵ of the Cleveland Wire Division, National Lamp Works, has carried out some very valuable tensile tests of

⁵ Private communication; the results of Mr. Sykes's tests will appear in the Bulletin of the A. I. M. M. E. for 1921.

relatively pure nickel wire at low and high temperatures from which the following values are chosen as representative. This wire was drawn from 0.095 to 0.025 inch diameter and annealed at 800° C; it contained 99.8 per cent nickel and 0.15 per cent iron (besides probably 0.4 per cent cobalt).

Temperature in degrees centigrade	Tensile strength		Elongation in 2 inches		Reduction of area	
	Slow	Rapid	Slow	Rapid	Slow	Rapid
	Lbs. in. ²	Lbs. in. ²	Per cent	Per cent	Per cent	Per cent
-185.....		84 000		22.0		58
25.....	60 000	62 000	22.0	23.5	75	75
100.....	56 000	57 000	20.3	20.3	73	71
200.....	50 000	51 000	15.5	18.7	68	75
300.....	50 000	51 000	17.5	14.0	75	79
400.....	43 000	47 000	17.3	19.5	75	80
500.....	34 000	36 000	19.5	20.0	75	75
600.....	25 000	29 000	15.5	19.5	65	60
700.....	17 000	21 000	15.5	14.0	60	60
800.....	13 000	17 000	15.5	15.5	45	48
900.....	9 000	11 000	15.5	20.0	39	48
1000.....	7 000	9 000	26.5	19.0	48	43

VII. EFFECT OF IMPURITIES ON THE PROPERTIES OF NICKEL

With reference to the effect which they exert upon the physical properties of nickel the ordinary impurities fall naturally into two classes; that is, those which are soluble in the solid state in nickel and those which are not. Those of the former class act in general only to increase more or less the hardness and strength of the metal, and of course to diminish its electrical conductivity. Those of the latter class affect chiefly the hot but also cold working properties of the metal.

CARBON.—Carbon is hardly to be looked upon as an impurity in nickel any more than it is to be so regarded in steel; it is an element which is never absent in the metal, and its presence is necessary, in the present state of the art, for the production of malleable nickel on a commercial scale.

The nickel-carbon equilibrium diagram has received some attention at the hands of investigators, but there are still many gaps in our knowledge of the constitution of this binary system. With increasing carbon content the melting point of pure nickel is progressively lowered from 1452 to 1311° C, at which nickel forms a eutectic with 2.2 per cent carbon in the form of graphite. The liquidus temperature then rises again with increasing carbon

content, and at 2100°C the metal absorbs 6.42 per cent carbon, apparently in the form of a carbide, Ni_3C (284), which is, however, rapidly decomposed at lower temperatures with formation of graphite. The equilibrium below the eutectic temperature has never been satisfactorily worked out; Ruff, Borman, and Keilig (285) state from the results of their investigations that the solubility of graphite in nickel in the solid state is not greater than 0.5 per cent at the eutectic temperature, but they give no information about the solubility at lower temperatures which presumably diminishes. Although we do not have the exact knowledge of the equilibrium at lower temperatures which would be desirable, it is known that the presence of carbon introduces no transformation such as that which occurs in steel and with which might be associated the possibility of altering profoundly the physical properties of the alloys by means of a suitable heat treatment.

Within the limits in which carbon is usually found in nickel it occurs in solid solution and merely increases the hardness and strength of the metal. It increases the ease of hot-working operations by making the metal tougher at these temperatures and less susceptible to edge cracking. On the other hand it increases the difficulties of cold working both because with increased carbon the metal is initially harder and also because it hardens more rapidly with progressive cold work. The effect of carbon in increasing the hardness of nickel is illustrated in Table 15.

TABLE 15.—Effect of Carbon on the Hardness and Tensile Strength of Nickel

Chemical composition					Tensile properties				Hardness		Remarks
C	Mn	Si	S	Fe	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell 3000 kg	Scleroscope	
Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Lbs./in. ²	Lbs./in. ²	Per ct.	Per ct.			
0.08	.....	0.04	0.025	0.63	22 000	69 000	46	50	103	10	Hot-rolled.
.26	0.48	.13	.016	.56	34 000	93 000	40	35	132	17	Do.
.19	.26	.33	.....	.68	.....	.....	.....	.....	131	15	Annealed.
.06	.21	.33	.....	.59	.....	.....	.....	.....	97	10	Do.

When the percentage of carbon exceeds 0.40 per cent the separation of graphite may take place, a change accompanied by a loss of malleability. Free graphite should not be present in good-quality malleable nickel. The statement that carbon is harmful to malleable nickel and that its presence should be avoided is not correct, but becomes so when the carbon is in form of graphite.

NICKEL OXIDE (NiO).—This compound can not be present in malleable nickel and is, therefore, in a sense not to be regarded as an impurity of it; on the other hand, the potential effect of it on the properties of the metal makes necessary certain procedure in the preparation and deoxidation of malleable nickel of the utmost importance. It does occur in shot and in blocks and occasions the complete lack of malleability of these forms of the metal.

The equilibrium of nickel and nickel oxide has not been systematically studied. The only mention of it is by Ruer and Kaneko (300) who state that the presence of NiO in molten nickel depresses the melting point by about 10°C and give a photomicrograph showing the eutectic structure of it in nickel. Apparently nickel dissolves several per cent of nickel oxide in the liquid state, which is completely insoluble in the solid state and separates out in the form of a eutectic. Fig. 1 shows the appearance of this eutectic in nickel blocks.

As nickel oxide is always found and probably is formed as well in molten nickel in process of being refined, it is necessary to remove it before pouring the metal into ingots for forging or rolling. This may be done by means of manganese, aluminum, or magnesium, but the latter element is by far the best and is generally used. It is introduced in the form of 1 to 2 inch rod either into the crucible or teeming ladle; it must be plunged to the bottom and stirred around briskly in order that it will not merely float to the surface and burn off. Approximately $1\frac{1}{2}$ ounces to the hundred pounds of metal is added; more magnesium will do positive harm, as it appears to make the melted metal thick and sluggish to pour.

TABLE 16.—Effect of Manganese on the Physical Properties of Hot-Rolled Nickel Rod

No.	Chemical composition					Tensile properties					Electrical resistivity
	C	Mn	Fe	Si	S	Proportional limit	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area	
	Per cent	Per cent	Per cent	Per cent	Per cent	Lbs./in. ²	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent	microhm-cm
1.....	0.06	3.00	0.62	0.22	0.018	20 000	23 500	74 100	51	60	14.5
2.....	.06	3.58	.62	.23	.018	22 500	23 700	74 400	50	62	.....
3.....	.06	4.40	.73	.27	.021	25 000	27 500	75 500	43	63	17.9
4.....	.06	5.06	.72	.28	.020	22 500	26 800	77 500	48	62	19.2
5.....	.07	6.78	.89	.34	.020	31 000	30 500	82 000	50	66	23.6
6.....	.08	6.84	.91	.35	.020	31 500	31 200	81 300	36	50	24.6
7.....	.10	9.18	.95	.42	.021	32 000	32 900	84 100	48	62	29.3
8.....	.10	9.24	.94	.41	.020	31 000	32 800	83 800	48	64	29.7

MANGANESE.—Manganese is generally absent from nonmalleable nickel but is added intentionally to malleable metal both because of its effect on its ultimate properties and because of its usefulness in decreasing manufacturing difficulties. It renders the metal less tender just after freezing and thus aids in the production of ingots free from "pulls" and hot cracks. It also increases the fluidity of the molten nickel and thus renders easier the production of ingots of good surface.

The advantages of its presence as far as ease of manufacturing is concerned are obtained with small additions. Added in larger amounts it increases the resistance of nickel to oxidation and renders it less susceptible to the action of sulphur in the fuels used in hot rolling. Thus it is the C and D grades of nickel containing from 1.50 to 6 per cent manganese which are largely used for the spark points of motor ignition systems.

The equilibrium of the system manganese-nickel has been studied by Zemczuzny, Urasow, and Rykowskoff (374) who find that the two metals are soluble in all proportions both in the solid and in the liquid state. This agrees with our rather meager knowledge of the properties of high manganese-nickel alloys. These may be rolled readily up to 10 per cent of manganese and probably beyond, although the 50 per cent alloy is known to be quite brittle. Within these limits the addition of manganese mildly increases the hardness and strength of nickel without materially decreasing the ductility. The addition of manganese, however, does decrease the electrical conductivity of nickel markedly (552); thus the resistivity of nickel, drawn and annealed, was increased from 12.43 microhm-cm to 28.0 and 51.2 microhm-cm with the addition of 10 and of 20 per cent respectively of manganese. Table 16 shows the effect of manganese on the tensile properties and resistivity of hot-rolled nickel rod.

SULPHUR.—The form in which the usual small amounts of sulphur occur in commercial nickel is not known, but it is present presumably as a sulphide of nickel or of manganese. Its presence in amounts above about 0.05 per cent decreases the ductility both hot and cold, and it should be held as low as possible in nickel intended for malleable ingots.

Judging therefore by its effect on the properties of the metals it is present in the form of a separate constituent, insoluble in the solid state in nickel. Bornemann (397, 398) has investigated the equilibrium of the system nickel-sulphur and finds that a

compound is formed, Ni_3S_2 , which is soluble in the liquid state in nickel but which forms a eutectic with it at 21.5 per cent sulphur and 644°C upon solidifying. The solubility of Ni_3S_2 in nickel in the solid state at the eutectic temperature is about 0.5 per cent and rapidly approaches zero at lower temperatures.

IRON.—This element is always present in commercial nickel due both to imperfect removal of the iron originally present in the ores and to the wear and solution of tools used in the roasting and refining furnaces. The amount present is usually less than 1 per cent and has no appreciable effect upon the properties of the metal. The system nickel-iron has been investigated by Guertler and Tammann (368), Ruer and Schüz (366, 367), and others who find that the metals form an uninterrupted series of solid solutions, with certain interesting anomalies described below.

COBALT.—This element in amounts up to 1 per cent and averaging about 0.4 per cent in American nickel is invariably found in nickel and is usually included in the figure given for the nickel content. It is soluble in the nickel in all proportions both in the liquid and in the solid state and in these amounts does not exert any appreciable effect upon the properties of nickel except probably the electrical resistivity.

SILICON.—According to Guertler and Tammann (394) this element forms a compound, Ni_3Si , with nickel which is soluble in molten nickel, but upon solidifying forms a eutectic with it at 10.6 per cent silicon and 1153°C . The solubility of this compound in the solid state in nickel is equivalent to 6 per cent of silicon at the eutectic temperature, decreasing to 2.5 per cent at 660°C and approaching lower values as the temperature decreases.

Silicon is always present in furnace-refined nickel in amounts generally under 0.25 per cent and has comparatively little effect in these amounts. In larger amounts the hardness of the metal is increased and its ductility decreased, and with increasing amounts the malleability, both hot and cold, is diminished and finally destroyed completely. This occurs at from 3 to 5 per cent of silicon.

VIII. TECHNOLOGY

1. CASTING

Nickel is cast from the furnace into open molds to produce blocks for remelting, into ingot molds after deoxidation with manganese and magnesium for the production of malleable nickel and into sand molds for nickel castings. It is also poured directly into water to form nickel shot.

For the production of castings, the metal in the form of blocks or shot may be remelted in crucibles or in an oil-fired or electric furnace with the addition of charcoal to reduce the oxide which is present and which is formed during remelting. When at the proper temperature, it is poured into a ladle and deoxidized in the same manner as for the production of malleable ingots and poured into the molds. The chief difficulty in the remelting of nickel is in the proper adjustment of carbon and oxide content of the molten metal prior to deoxidation, which is called "bringing the metal to pitch;" this operation consequently requires the services of an experienced furnace operator and may be an absolute failure without him.

Platers' anodes are melted with carbon and may be poured at a much lower temperature than is malleable nickel and do not require deoxidation treatment of any kind; they are consequently much easier to handle in the foundry than is low-carbon metal.

The molding of nickel castings follows the practice used for steel castings, generally speaking, an allowance of one-fourth inch to the foot being made for shrinkage.

Other than the process of deoxidation, which is absolutely essential, the production of malleable nickel ingots requires no novel operations not known for instance in the steel industry. Deoxidized nickel solidifies without blowholes but with a pronounced pipe, which renders the use of proper risers or hot-tops and properly designed molds necessary.

2. ROLLING, FORGING, ANNEALING

In the hot-working of nickel, both the temperature and the condition of the heating flame should be subject to careful control. The temperature for preheating and rolling should be from 1100°C to 1180°C and ingots should not be subjected to temperatures much in excess of this, as they become somewhat hot-short at higher temperatures. Below this temperature the metal may be too hard to roll satisfactorily. The flame used for heating should be as nearly neutral as possible, and a low-sulphur fuel (oil) is essential for successful heating.

For hot-rolling bars and rods of the usual cross sections, the same designs of rolls as are used for steel may be and are employed with success. Pure nickel and nickel alloys of high nickel content are very easily "guide marked" when hot.

The remarks of the first paragraph above apply also to the forging of nickel. Nickel is much more successfully forged under the hammer than under a press; in fact, the metal has a pronounced

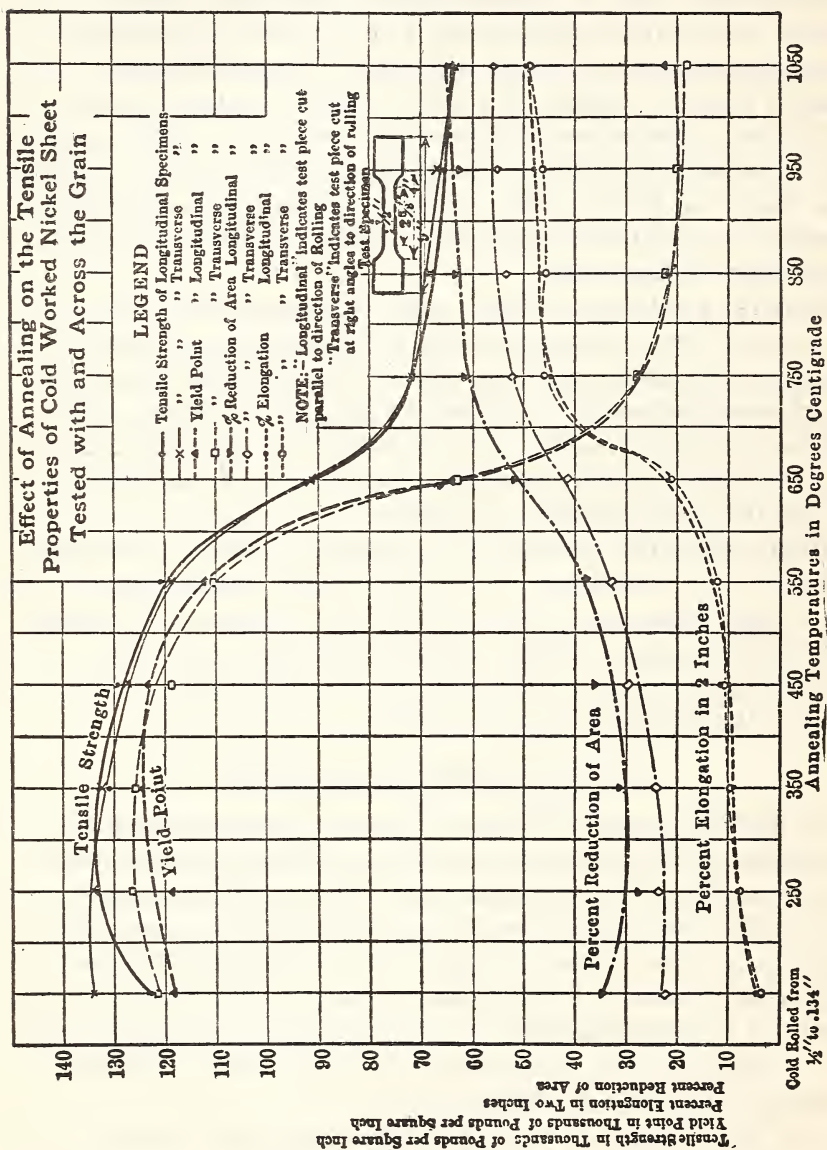


FIG. 10.—The annealing of nickel (Price and Davidson, 36); its effect upon the tensile properties

tendency to crack under the slow action of the press, which may be due to the fact that the surface cools more readily than under the quick blows and short contact of the hammer.

In order to soften nickel which has been worked cold, it must be heated to at least 750°C , the minimum temperature of the annealing range, allowed to remain in the furnace until thoroughly heated throughout; it may be cooled rapidly or slowly, as desired, as there is no alteration in the properties of the metal produced by cooling after annealing. For the commercial annealing of nickel a temperature of 900°C should be used, as this will ensure a more thorough and homogeneous anneal than might be accomplished at lower temperatures.

Price and Davidson (36) have studied the annealing of nickel of commercial pure grade (A) and their results are shown in Fig. 10. The annealing range for the metal is from 600 to 800°C ; commercially the metal is usually annealed at 900°C .

Whenever possible the metal should be annealed in tight boxes to prevent the formation of oxide, and any oxide formed may be reduced by the creation of a reducing atmosphere in the box, either by the presence of a small amount of charcoal or by the admission of some reducing gas. When annealing is done in this manner no pickling is required, and on account of the difficulty and expense pickling should only be adopted as a last resort.

If necessary, pickling may be accomplished by the use of sulphuric acid with some oxidizing agent, such as ferric sulphate or chromic acid, at a temperature around 60 to 70°C , but it is a slow and tedious process.

3. WELDING AND SOLDERING

Nickel can not be smith-welded owing to the formation of a coating of nickel oxide which can not be fluxed, and which prevents the adherence of the two surfaces to be welded. On the other hand, under conditions under which a reducing atmosphere may be maintained the metal may be welded, such as by the use of the oxy-acetylene torch, or by electric resistance welding. It is by the latter process that nickel wire is welded to iron wire to form tips or points for spark plugs.

Under suitable reducing conditions nickel may be plastically welded to steel, and an interesting process, invented by Dr. Fleitman about 35 years ago, of producing nickel-coated steel sheets is based upon this possibility. A steel sheet bar, about three-fourths inch thick, is cleaned and pickled and placed between two thinner plates of clean nickel. Around the whole is wrapped thin steel sheet, which protects the nickel against oxidation and is dissolved off by later pickling. The compound sheet

bar is heated in a reducing atmosphere and then rolled and cross-rolled into a solid, compound sheet. Needless to say the nickel coating so produced is thicker and more durable than electrolytically deposited metal.

4. ELECTRODEPOSITION

Outside of the production of electrolytic nickel, the chief chemical application of nickel deposition is in the nickel-plating of steel, brass, zinc, and numerous alloys, generally in the form of castings or stampings, partly for protection against corrosion but primarily for the improvement of appearance. Its chief value for this purpose lies in its relative hardness and its resistance to abrasion and atmospheric corrosion. Nickel is used to a limited extent in electrotyping, in which case it may be deposited directly upon the wax or lead mold, producing a true nickel electrotype; or it may be deposited upon the face of a finished copper plate, making a nickel-plated electrotype. In general, the function of the nickel upon electrotypes is to give a harder wearing surface, which is also more resistant than copper to the action of the colored inks frequently employed. The production of nickel articles, for example, tubes, etc., by deposition upon wax or other fusible molds has never been commercially successful, though processes recently devised appear promising for this purpose.

The principal salts of nickel used in plating and electrotyping are nickel sulphate and nickel-ammonium sulphate (known commercially as "single" and "double" salts, respectively). The nickel-ammonium sulphate has the advantage of better conductivity but the disadvantage of lower solubility than the nickel sulphate. Mixtures of the two are frequently used. In 1878 Weston patented the use of boric acid in nickel baths, which has come into quite general use. The presence of the boric acid appears to favor more uniform operation of the baths, and to produce brighter deposits. Experiments of L. D. Hammond (222) indicate that the essential function of the boric acid, is the maintenance of a uniform slight acid or hydrogen-ion concentration in the solution. He found that good deposits can be obtained from solutions slightly acidified with strong or weak acids, none of which, however, is so suitable as boric acid for continued service.

As noted on page 24 pure nickel exhibits in a marked degree the phenomenon of passivity when it is made the anode in most acids or salts. In consequence the use of pure nickel anodes in nickel-

sulphate solutions would soon bring about an impoverishment in nickel and the liberation of free sulphuric acid. Hence it has been customary to add to nickel anodes, appreciable amounts of iron, carbon, and tin, which by local action increase the solution tension of the nickel. Incidentally they lower the fusing point, and thereby facilitate the casting of the nickel anodes. Many of the nickel anodes in use contain only 88 to 90 per cent of nickel, thus avoiding the contamination of the solutions and accumulations of slimes. This development has been rendered possible by the addition of chlorides, or more recently of fluorides, to nickel baths, both of which reduce anode passivity and increase the corrosion. Chlorides of sodium, ammonium, nickel, or magnesium are frequently added.

The fluorine is usually added in the form of hydrofluoric acid, though it is preferable first to neutralize this acid with nickel carbonate, thus forming nickel fluoride.

In addition to aiding in anode corrosion, the presence of sodium or ammonium chloride increases the conductivity of the solutions. Other salts are sometimes added to nickel solutions to increase the conductivity; for example, ammonium sulphate (in the form of, or in addition to nickel-ammonium sulphate) and magnesium sulphate. Salts of organic acids, such as tartrates, citrates, etc., which have also been added, may serve (1) to regulate the acidity, (2) to dissolve basic compounds, especially of iron, and (3) to reduce the rate of chemical deposition of nickel by more positive metals. The latter function is especially useful in the nickel-plating of zinc and zinc alloys.

In general nickel-plating has been conducted at low temperatures, but Watts has shown that in solutions containing nickel chloride or sulphate and boric acid hot solutions may be employed to advantage, and may permit the use of much higher current densities.

The following formulas illustrate the various types of nickel baths in actual commercial use. It is not implied, however, that these formulas will always be satisfactory, much less that they are the best for a given class of work.

	Grams per liter	Ounces per gallon
(1) Nickel electrotyping:		
Nickel ammonium sulphate.....	45	6
Nickel sulphate.....	15	2
Sodium chloride.....	7.5	1
(2) Nickel-plating—double-salt solution:		
Nickel ammonium sulphate.....	90	12
Ammonium chloride.....	22.5	3
Boric acid.....	15	2
(3) Nickel-plating—single-salt solution:		
Nickel sulphate.....	120	16
Ammonium chloride.....	22.5	3
Boric acid.....	15	2
(4) Nickel-plating (Watts)—for high current density, or in hot solutions:		
Nickel sulphate.....	240	32
Nickel chloride.....	15	2
Boric acid.....	30	4
(5) Nickel-plating on zinc (Hammond):		
Nickel sulphate.....	240	32
Nickel chloride.....	15	2
Boric acid.....	30	4
Sodium citrate.....	175	23

PART B. ALLOYS OF NICKEL

IX. EQUILIBRIUM OF BINARY ALLOYS OF NICKEL

The constitution of most of the important binary-alloy series with nickel has been investigated fairly completely and the principal results of these investigations are given in Tables 17, 18, 19, 20. It is observed that nickel has a strong tendency to form solid solutions with other metals, either of limited compositions or in all proportions. It is, structurally speaking, perhaps mainly for this reason that the metal forms a constituent of so many commercially useful ferrous and nonferrous alloys.

TABLE 17.—Binary Alloys of Nickel Having Limited Miscibility in the Liquid State

Nickel and—	Temperature of beginning melting		Solubility in solid state of—	
	Temperature	Composition	(x) in nickel	Nickel in (x)
	° C	Per cent Ni	Per cent (x)	Per cent Ni
Lead.....	326	97-0	3	0.7
Silver.....	961	100-0	.....	.....
Thallium.....	320	97-0	3	0

TABLE 18.—Binary Alloys of Nickel in Which the Two Metals Form a Simple Eutectiferous Series

Nickel with—	Eutectic		Solubility at eutectic temperature	
	Temperature	Composition	(x) in nickel	Nickel in (x)
	° C	Per cent Ni	Per cent (x)	Per cent Ni
Gold.....	950	27	16?	6?

TABLE 19.—Binary Alloys of Nickel in Which the Two Metals Are Soluble in All Proportions in the Solid State

Nickel and—	Melting point of the two metals	Maximum or minimum melting point	Composition at maximum or minimum melting point
	° C	° C	Per cent Ni
Chromium.....	1452-1520	1290	40
Cobalt.....	1452-1480	.....	.....
Copper.....	1452-1083	.....	.....
Iron.....	1452-1530	1425	70
Manganese.....	1452-1260	1000	44
Palladium.....	1452-1549	.....	.....
Platinum.....	1452-1755	.....	.....

TABLE 20.—Binary Alloys of Nickel in Which the Two Metals Form One or More Compounds

Nickel and—	Compounds formed	Nickel rich alloys				(x) rich alloys			
		Compound	Solubility of compound in nickel	Eutectic		Compound	Solubility of compound in (x) at eutectic temperature	Eutectic	
				Temperature	Composition			Temperature	Composition
			Per ct. (x)	°C	Per ct. (x)		Per ct. Ni	°C	Per ct. Ni
Aluminum...	NiAl; NiAl ₂ ; NiAl ₃ .	NiAl....	14	^a 1370	13	NiAl ₃ ...	(?) 0	630	7
Antimony.....	SbNi ₃ ; Sb ₂ Ni ₅ ; SbNi	Sb ₂ Ni ₅ (1)	7.5	1100	35	SbNi....	0	612	4
Arsenic.....	NiAs ₂ ; Ni ₃ As ₂ ; Ni ₃ As ₂ ; NiAs	Ni ₃ As ₂ ..	5.5	898	28	.....	.....	.....	.....
Bismuth.....	NiBi; NiBi ₃	NiBi....	2	^a 655	.....	NiBi ₃ ...	0	272	0
Boron.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cadmium.....	NiCd ₄.....	.....	.....	.....	.....	NiCd ₄ ...	0	321	0
Carbon.....	Ni ₃ C(?).....	.....	.....	.....	.....	.....	.....	.....	.....
Magnesium..	Ni ₂ Mg; NiMg ₂	Ni ₂ Mg..	0	1082	12	NiMg ₂ ...	0	512	32
Molybdenum.	MoNi.....	MoNi....	33	1300	50	.....	.....	.....	.....
Phosphorus...	Ni ₃ P; Ni ₅ P ₂ ; Ni ₂ P..	Ni ₅ P ₂ ...	0	880	12	.....	.....	.....	.....
Selenium.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Silicon.....	Ni ₃ Si, Ni ₂ Si, Ni ₃ Si ₂ , NiSi.....	Ni ₃ Si....	6	1153	10.6	.....	.....	.....	.....
Sulphur.....	Ni ₃ S ₂ ; NiS.....	Ni ₃ S ₂ ...	0.5	644	23	.....	.....	.....	.....
Tellurium.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Tin.....	Ni ₃ Sn; Ni ₂ Sn; Ni ₅ Sn ₂	Ni ₃ Sn....	15	1135	33	Ni ₃ Sn ₂ ..	0	229	(?) 1
Zinc.....	NiZn; NiZn ₃	NiZn....	30(?)	^a 1035	.....	NiZn ₃ ...	0	419	0

^a Peritectic.

X. COMMERCIAL ALLOYS

1. MONEL METAL

This alloy was introduced by the International Nickel Co. about 1905 and named after its then president, Ambrose Monell. It is a natural alloy produced directly from Canadian Bessemer matte by roasting and reducing with charcoal and has the following average composition:

	Per cent
Nickel.....	67
Copper.....	28
Other metals (iron, manganese, silicon)	5

Several grades of this metal are produced for different purposes, of which the following typical analyses are given:

TABLE 21.—Typical Analyses of Monel Metal

Material	Constituents				
	C	Mn	Fe	Si	S
	Per cent	Per cent	Per cent	Per cent	Per cent
Rolled Monel metal sheet.....	0.11	0.15	1.76	0.18	0.026
Rolled Monel metal rods.....	.26	1.78	2.00	.20	.035
Monel metal wire.....	.12	1.66	2.10	.13	.025
Monel metal castings.....	.18	.25	1.90	1.06	.03

It will be noted that the wire is made with low carbon content in order that it may be readily cold-drawn, whereas hot-rolled rods are produced with somewhat more carbon in order to increase the ease of their hot-rolling.

The practice in producing castings and malleable ingots of this alloy follows very closely that of the production of malleable nickel and nickel castings which has already been described. After bringing to pitch in the furnace—that is, adjusting the carbon and oxide content—it is deoxidized with manganese, or ferromanganese, and magnesium, the latter being used in the same proportions as for nickel and poured into ingot molds or sand castings. Unless so deoxidized it is, generally speaking, not malleable and can not be rolled or forged.

The ingots so produced may be rolled or forged at from 1040 to 1100° C, by using the same precautions as in the case of nickel against oxidation and absorption of sulphur during heating. Rods are produced by hot rolling or forging; from these bright, cold-drawn rods are also produced by close-annealing and cold-drawing. Wire is drawn from hot-rolled, close-annealed wire rod about one-fourth to three-eighths inch in diameter. Annealing of hot-rolled Monel metal preparatory to cold-rolling or drawing is carried out at about 900° C, preferably in charcoal boxes, to prevent scaling. Light scaling may, however, be removed by pickling with sulphuric acid and ferric sulphate, as in the case of nickel, but it is a slow and rather unsatisfactory process.

The metal is on the market in the usual commercial forms,⁶ sheet, bars, wire, and various special manufactured forms, such as wire cloth, screens, nails, chain, bolts, nuts, golf-club heads, and in the form also of castings.

⁶ Booklets by the Monel Metal Products Co. and by the International Nickel Co. describe the properties and uses of this alloy.

(a) METALLOGRAPHY.—The elements entering into the composition of Monel metal form with each other a continuous series of solid solutions, consequently the structure of the annealed or rolled metal is quite simple and similar to that of nickel, consisting of grains of solid solution with small particles of the oxides⁷ of magnesium and manganese. This is illustrated in Fig. 11; the typical structure of cold-drawn rods of Monel is illustrated in Fig. 12. The structure of cast Monel metal is, however, quite different from that of cast nickel and is that characteristic of solid solutions; it has the cored or dendritic structure illustrated in Fig. 13. The darker portions are richer in copper than the light areas, due to the selective method of solidification. This heterogeneity of concentration is relieved by annealing and by the processes incident to hot forging or rolling.

Monel metal may be etched with satisfactory results by the use of the 50 per cent nitric acid solution containing 25 per cent of glacial acetic acid, described above. It is also attacked by ferric-chloride solutions, and such solutions are also suitable for metallographic etching; a solution containing 1 g FeCl_3 and 2 cc concentrated HCl , diluted to 2 or 3 volumes with water, is recommended.

Monel metal exhibits the same phenomenon as does nickel of intercrystalline brittleness produced by exposure at rolling temperature to the action of oxidizing or sulphurizing gases and which was described on page 16.

(b) USES AND APPLICATIONS.—The principal properties of this metal which render it of commercial value are perhaps the following: Resistance to corrosion, the bright nickel finish which it takes and retains, its strength and hardness—particularly at high temperatures, and its resistance to erosion by water and steam.

Monel metal resists excellently the action of ammonia, solutions of ammonium hydroxide, fused and dissolved caustic alkalis and carbonates, fatty and many other organic acids, sea water, solutions of neutral salts such as alum, sulphates, chlorides, etc., gasoline and mineral oils generally, phenol and cresols, photographic chemicals, urine, dry mercury, dyeing solutions, alcoholic and other beverages. It resists fairly well the action of sulphuric, weak phosphoric, hydrocyanic acids, hydrofluoric, acetic and citric acid, ferrous sulphate, and dry chlorine. It is not resistant to the action of hydrochloric and nitric acids, molten lead and

⁷ Or possibly other compounds.



FIG. 11.—Microstructure of rolled Monel metal rod. $\times 100$

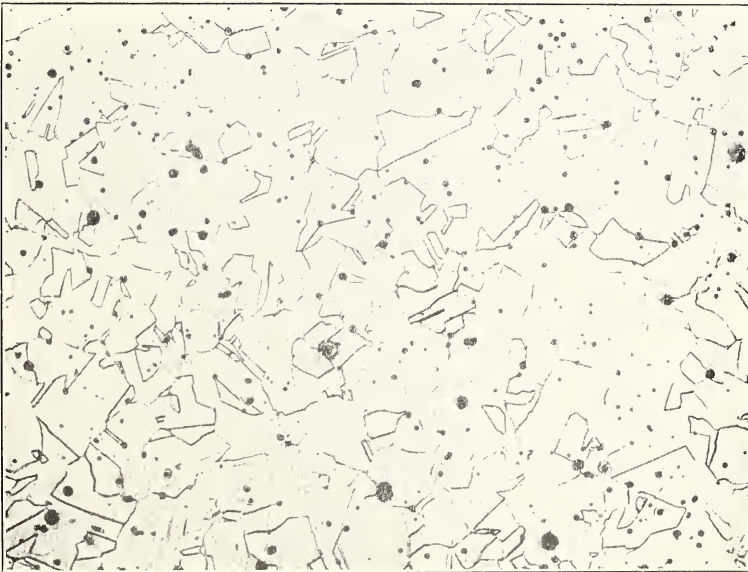


FIG. 12.—Microstructure of cold-drawn Monel metal rod. $\times 150$

Bureau of Standards Circular No. 100



FIG. 13.—Microstructure of cast Monel metal. $\times 100$

zinc, potassium cyanide, fused or in solution, sulphurous acid, ferric chloride, and chromic acid.

Monel-metal sheet showed the following losses in weight upon exposure to the action of boiling acetic acid for eight hours:

Loss in weight per square inch per hour, in 10 per cent acid = 0.07 mg

Loss in weight per square inch per hour, in 26 per cent acid = 0.8 mg

Loss in weight per square inch per hour, in 56 per cent acid = 1.1 mg

Loss in weight per square inch per hour, in 90 per cent acid = 1.2 mg

It lost 0.076 mg per square inch per day during eight months' exposure to cold glacial acetic acid.

Because of its relative incorrodibility it has been used to some extent for roofing material. The roof of the Pennsylvania Terminal in New York City is covered with Monel sheet selected because of its superiority over other roofing materials demonstrated during a 10-year test. It is also used for window screens for the same reason.

Both rods and castings are used to a large extent in the manufacture of pumps, pump liners, rods, valves, etc., for handling sea water, mine waters, and acid and alkaline corrosive solutions generally. One of the principal applications of the metal is in the construction of pickling tanks and crates for pickling steel; rods are used for this purpose and have apparently proved superior to any other material. In this connection the results of corrosion tests of Monel-metal rod in pickling acid are of interest. Rods exposed for 90 days to the action of continually renewed 6° Be (6 to 7 per cent) sulphuric acid at 74° C lost weight at the average rate of 0.0045 g per square inch per day, corresponding to the removal of a layer 0.00003 inch thick per day; the removal of a 0.1 layer would therefore by extrapolation require about 10 years. In fact, Monel-metal pickle pins and rods have been removed from service after eight years and found to show practically no evidence of corrosion. Their average life is perhaps three years. On account also of its resistance to corrosion it is used in the construction of mining machinery, mine screens, dyeing machinery and equipment, and in the chemical and oil industries for miscellaneous parts exposed to severely corrosive conditions.

Monel metal takes and retains a finish almost identical with that of pure nickel and is for this reason much used for small fittings, trimmings, and stampings, for golf-club heads, and for knives.

This property in conjunction with its resistance to corrosion by substances used in preparation of foods and in washing have made it valuable for the construction of certain cooking utensils and for washing tanks, cream-separator machinery, etc.

The resistance of the alloy to steam erosion and its strength at high temperatures, which seems to be higher than that of the steels or bronzes, have caused its extensive application in the production of steam pressure valves and steam-turbine blading. For these purposes it is well suited also by reason of the fact that its thermal expansivity is approximately equal to that of steel with which it is usually associated in such construction.

Marine propellers have been cast of Monel metal. In connection with its quite widespread use in naval construction it may be recalled that the steam yacht *Sea-Call* was covered with Monel sheathing, in this particular case unsuccessful for the reason that the galvanic action between it and the exposed steel parts of the hull caused accelerated corrosion of the latter. It is obvious that construction of this sort must be avoided, involving Monel metal and steel in galvanic contact and exposed to the action of an electrolyte such as sea water or other aqueous solutions; the entire construction should be of Monel.

Monel metal is remarkably resistant to oxidation even at high temperatures (750° C) and is used for electrical resistance and spark-plug wire and other parts exposed to high temperatures. Monel metal is made up into screen of various types, into filter cloth used in filtering corrosive liquids, and into screw machine products of all kinds.

(c) PHYSICAL PROPERTIES—The physical properties of Monel metal are described by the International Nickel Company (450). Its melting point is about 1360° C, its density in the rolled condition, 8.97 (0.323 pound per cubic inch). The mean coefficient of thermal expansion between 20 and 100° C, as well as between 20 and 400° C, is 0.000015. For the latest data, see second table on page 20. Its electrical resistivity in the form of wire is 42.5 microhm-cm (256 ohm-mil-foot), temperature coefficient of resistivity, 0.0019 per degree centigrade. The thermal conductivity of Monel metal is one-fifteenth that of copper or about 0.06 cal./cm³/sec/°C. The optical reflectivity of Monel metal is not markedly different from that of nickel; values for its reflectivity are given in Table 11.

The mean specific heat of Monel metal between 20° C and its melting point is 0.127 cal. per gram according to recent determina-

tions of Dr. W. P. White, who finds its latent heat of fusion to be 67 cal./gram.

Monel metal is slightly magnetic and its permeability varies markedly with composition and mechanical and heat treatment. An annealed rod of Monel metal containing 66.1 per cent nickel, 28.8 per cent copper, 2.68 per cent iron, 1.91 per cent manganese, 0.22 per cent carbon, and 0.29 per cent silicon gave the following values of magnetic induction in recent tests by Dr. Chas. W. Burrows.

TABLE 22.—Magnetic Induction of a Monel Metal Rod

Magnetizing force	Magnetic induction	Magnetizing force	Magnetic induction	Magnetizing force	Magnetic induction
Gausses	Gausses	Gausses	Gausses	Gausses	Gausses
1	413	10	1203	75	1300
2	699	20	1244	100	1317
4	989	50	1282	150	1346

With varying treatment values of the magnetic induction for a magnetizing force of 50 gaussess, varying from 500 to 2000, may be obtained.

The modulus of elasticity (Young's modulus) is 22 000 000 to 23 000 000 pounds per square inch. The hardness varies with the form and condition of the metal as may be seen in Table 23.

TABLE 23.—Hardness of Monel Metal Products

Material	Scleroscope hardness universal hammer	Brinell hardness 0.10 mm ball	
		500 kg	3000 kg
Hot-rolled Monel-metal rods.....	20-30	100-130	145-170
Cold-drawn Monel-metal rods.....		150-170	180-200
Cast Monel metal.....	20-25	90-100	.....
Monel-metal sheet.....			.....
Annealed Monel metal.....	15-20	80-100	.....

The tensile properties of Monel metal vary also with the composition, condition, and size of the rod; values are given in Table 25. The proportional limit of hot-rolled rods averages from 30 000 to 45 000 pounds per square inch, that for castings from 15 000 to 25 000 pounds per square inch.

Specifications are issued by the U. S. Navy Department for this alloy in its different forms and from which further information may be obtained about its tensile properties. (See appendix.)

The torsional properties of Monel metal hot-rolled rods have the following range of values:

Shearing stress at outermost fiber at—	Lbs./in. ²
Proportional limit.....	20 000-40 000
Yield point.....	50 000-80 000
Maximum.....	75 000-95 000

Direct shearing tests on hot-rolled Monel metal rods carried out in the engineering laboratory of Lehigh University gave the following average results:

TABLE 24.—Shear Tests of Monel Metal Rods

Diameter of test bar	Single shear maximum stress	Double shear maximum stress
	Lbs./in. ²	Lbs./in. ²
1-inch.....	55-61 000	115-127 000
¾-inch.....	45-50 000	90-103 000

Compression tests of rods and castings give the following results:

Property	Rods	Castings
	Lbs./in. ²	Lbs./in. ²
Proportional limit.....	25 000-50 000	15 000-25 000
Yield point.....	60 000-70 000	20 000-30 000

TABLE 25.—Tensile Properties of Monel Metal

Material	Average tensile properties			Average range of tensile properties			
	Yield point	Tensile strength	Elongation in 2 inches	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area
Hot-rolled rods:	Lbs./in. ²	Lbs./in. ²	Per cent	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
Up to 1 inch in diameter.	63 100	94 600	40	50-75 900	85- 110 000	28-55	45-65
1½ to 1¾.....	62 000	93 000	39				
1¾ to 2¾.....	50 100	87 700	42				
2¾ to 3½.....	43 800	85 300	44				
Over 3½.....	47 300	84 800	43				
Castings.....	37 100	72 300	34	32-44 000	65- 85 000	25-45	.....
Annealed sheet.....					60- 75 000	30-40	.....
Cold-drawn rods.....				60-80 000	87- 96 000	30-40	50-65
Wire:							
Annealed.....					60- 75 000		
Hard-drawn.....					110-150 000		

Very few tests have been made of the resistance of Monel metal to the action of alternating stresses but the indications of a few tests are that hot-rolled rods about 1 inch in diameter will withstand approximately 10 000 000 complete reversals of stress; that is, from tension to compression at 25 000 pounds per square inch maximum fiber stress, these tests having been made in the White-Souther machine.

The effect of temperature on the tensile and torsional properties of Monel metal has been studied by Bregowsky and Spring (195), and by Arnott (455), whose results are given in Tables 26, 27, and 28.

TABLE 26.—Tensile Properties of Monel Metal and 30 per cent Nickel Steel at Higher Temperatures (Bregowsky and Spring, 195)

Temperature in degrees centigrade	Rolled Monel metal				Rolled 30 per cent nickel steel			
	Tensile strength	Elastic limit	Elongation in 2 inches	Reduction in area	Tensile strength	Elastic limit	Elongation in 2 inches	Reduction in area
	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
21.....	104 900	78 350	31.3	61.7	94 498	39 850	51.2	59.8
149.....	97 400	58 500	29.7	57.8	97 000	37 100	64.1	65.0
233.....	97 800	58 690	29.7	51.0	84 950	32 250	62.5	65.0
275.....	96 400	58 400	32.8	59.5	83 000	26 200	59.4	66.8
317.....	89 600	57 950	32.8	59.5	69 575	25 650	56.3	72.6
399.....	67 600	42 550	28.1	58.1	45 650	21 100	43.0	59.0
510.....	.....	.....	.....	.....	.....	.....	.....	.....
555.....	47 200	26 800	28.1	60.7	36 350	15 500	37.5	55.7

Arnott (455) gives the values shown in Table 27 as the average of 18 tests:

TABLE 27.—Tensile Properties of Monel Metal at High Temperatures (Arnott, 455)

Temperature in degrees centigrade	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Lbs./in. ²	Lbs./in. ²	Per ct.	Per ct.
20.....	92 700	47 700	51	69
320.....	86 200	38 100	48	62
410.....	75 700	35 600	49.5	63
500.....	64 300	34 100	45	56
630.....	36 300	23 300	33	.....
700.....	23 100	17 700	27	36
905.....	6 300	3 600	27	28

TABLE 28.—Torsional Properties of Monel Metal at Higher Temperatures (Bregowsky and Spring, 195)

Material	Temperature	Torsional strength	Elastic limit	Angle of twist
	° C	Lbs./in. ²	Lbs./in. ²	
$\frac{7}{8}$ -inch rolled Monel metal.....	21	94 610	45 510	12 turns 150°
	196	83 030	33 940	5 turns 0
	317	72 290	31 300	5 turns 205
	426	40 610	10 910	6 turns 240
$1\frac{1}{2}$ -inch rolled Monel metal.....	21	91 990	37 780	11 turns 150
	196	78 030	36 140	4 turns 320
	317	54 210	19 800	4 turns 340
		59 591	26 123	4 turns 90
		426	38 600	7 turns 50

It is evident that Monel metal retains its strength to a remarkable extent at higher temperatures as compared with brasses, bronzes, and steel.

Webster (481) has studied the effect of cold-rolling on the tensile properties of Monel metal and has given the following values:

TABLE 29.—Effect of Cold-Rolling on Tensile Properties of Monel Metal

Material	Tensile strength	Elongation in 4 inches	Reduction of area
	Lbs./in. ²	Per ct.	Per ct.
Normalized Monel.....	79 000	26	35
Same after 20 per cent reduction.....	102 000	4	22
Same after 40 per cent reduction.....	118 000	3	18
Same after 60 per cent reduction.....	132 000	2	17

The discussion above on the effect of impurities on the properties of nickel applies with almost equal force to Monel metal. Carbon, as in the case of nickel, acts to harden the metal and render it easier to roll and forge hot, but hardens it and makes it more difficult to roll cold. The separation of graphite begins at a somewhat lower content of carbon than in the case of nickel, viz, in the neighborhood of 0.35 per cent.

Although a long, tough chip is produced in the machining of this metal it may readily be machined when proper conditions are observed. Tools are required of high-grade, high-speed steel and should be ground with large rake or lip and kept sharp. It may be machined either dry or with lubricant, and a good average speed for general work is from 50 to 60 feet per minute with a one-eighth-inch cut and a one-thirty-second-inch feed.

Monel metal may be soldered and brazed in the same manner as is iron or steel and it may be acetylene welded. The welded joint will, however, not be as strong as the original metal and will have little ductility. Ordinary Monel wire rod may be used as

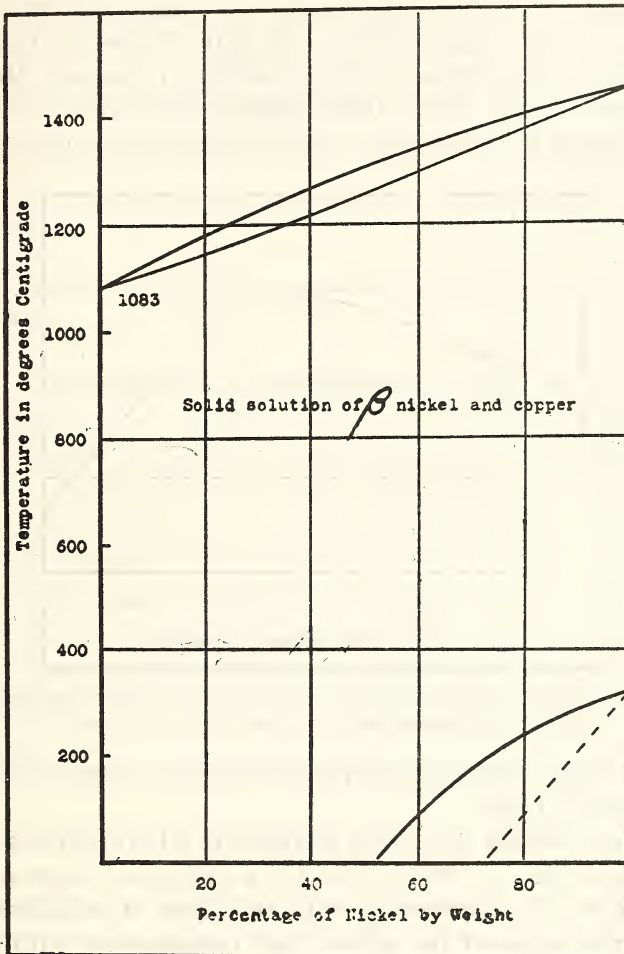


FIG. 14.—Equilibrium diagram of copper-nickel alloys according to Guertler (259)

welding rod. Acetylene welding of this metal as well as of nickel should be executed with a nearly neutral flame as the metal is highly sensitive at these temperatures to the presence of oxygen. Welded Monel metal and nickel tubes are being manufactured by the oxyacetylene process.

2. COPPER-NICKEL ALLOYS

These are undoubtedly among the earliest alloys of any sort known to man. Thus Muspratt⁸ mentions Bactrian coins containing 77 to 78 per cent copper and 22 to 23 per cent nickel dating from 235 B. C.; this composition is almost identical with our present nickel-coinage alloy. In spite of their antiquity the pure copper-nickel alloys have not perhaps come into the commercial prominence which their unusual properties should give them, although the recent war, with its large requirements of these

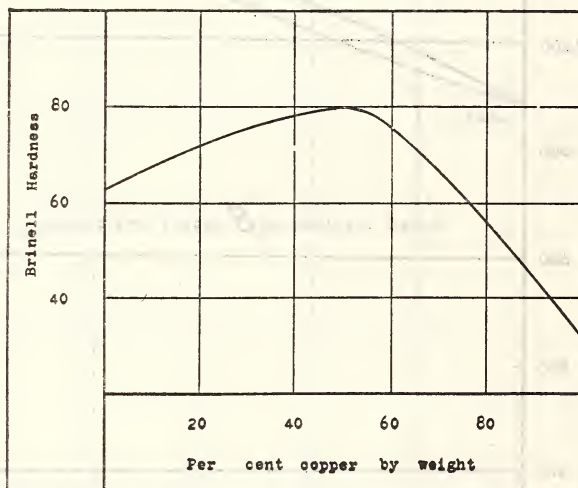


FIG. 15.—The hardness of copper-nickel alloys according to Kurnakov and Rapke (321).
Rolled and annealed samples; 10 mm ball, 500 kg load

alloys for bullet jackets and driving bands, has served to stimulate interest in them.

Nickel and copper form solid solutions in all proportions as may be seen from Fig. 14, which gives the equilibrium diagram of this binary series. In conformity with this type of equilibrium the physical properties of the alloys vary continuously with composition, maximum and minimum values being encountered within the series. Figs. 16 and 17 show the variation of electrical resistivity, its temperature coefficient and the thermoelectromotive force with composition of copper-nickel alloys.

Throughout the entire range of composition the alloys are ductile and malleable; their tensile strength and hardness reaches a maximum in the neighborhood of 50 per cent of copper; this is

⁸ *Chemie*, 6, p. 1195; 1898.

seen from Fig. 15. Table 30 gives typical values of the tensile properties for commercial compositions of copper-nickel alloys in different forms.

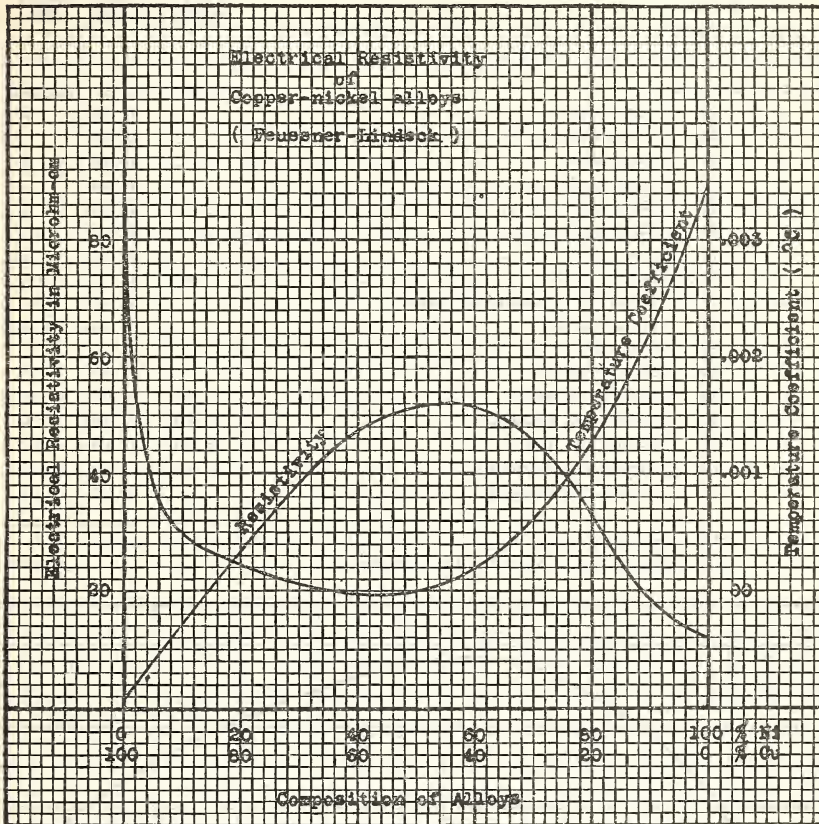


FIG. 16.—The electrical resistivity of copper-nickel alloys according to Feussner and Lindeck (342)

Baucke (328) has shown that small amounts of nickel increase the toughness of copper as indicated by the notch-bar impact test. He obtains the following results on forged and annealed test bars:

	Specific impact work in kilogram-meters
Electrolytic copper.....	14.1
0.17 per cent nickel.....	20.0
.31 per cent nickel.....	22.0
1.52 per cent nickel.....	28.0

Even in small amounts nickel decolorizes copper (and its alpha alloys). Thus bullet-jacket stock containing 15 per cent of nickel is practically white when freshly cut or polished.

TABLE 30.—Typical Values of the Mechanical Properties of Commercial Cupro-nickel Compositions

Chemical composition		Form	Yield point	Tensile strength	Elongation
Ni	Cu				
Per cent	Per cent		Lbs./in. ²	Lbs./in. ²	Per cent
2	98	Tubes, soft ^a		39 200	44
2	98	Tubes, hard ^a		63 500	5.5
5	95	Sheet, soft ^a		39 200	50
5	95	Sheet, hard ^a		67 500	4
20	80	Sheet, soft ^a		47 200	35
20	80	Sheet, hard ^a		90 000	4
25	75	Sheet, soft ^a		60 500	31
2.5	97.50	Driving band ^b	14 340	31 770	^a 69.6
2.5	97.50	Wire (0.08 inch diameter), hard ^b		72 150	^a 1.6
10	90	Strip, annealed ^b		48 450	^c 23.4
15	85	Strip, hard ^b		71 000	^c 3
15	85	Strip, annealed ^b		47 000	^c 23
20	80	5/8-inch rod, hard ^b	57 800	61 500	^c 14.8
20	80	5/8-inch rod, annealed ^b	13 000	47 600	^c 40
25	75	5/8-inch rod, hard ^b	58 000	64 000	^c 17
25	75	5/8-inch rod, annealed ^b	21 000	51 600	^c 39
40	60	1/8-inch rod, annealed ^b		69 400	^c 23

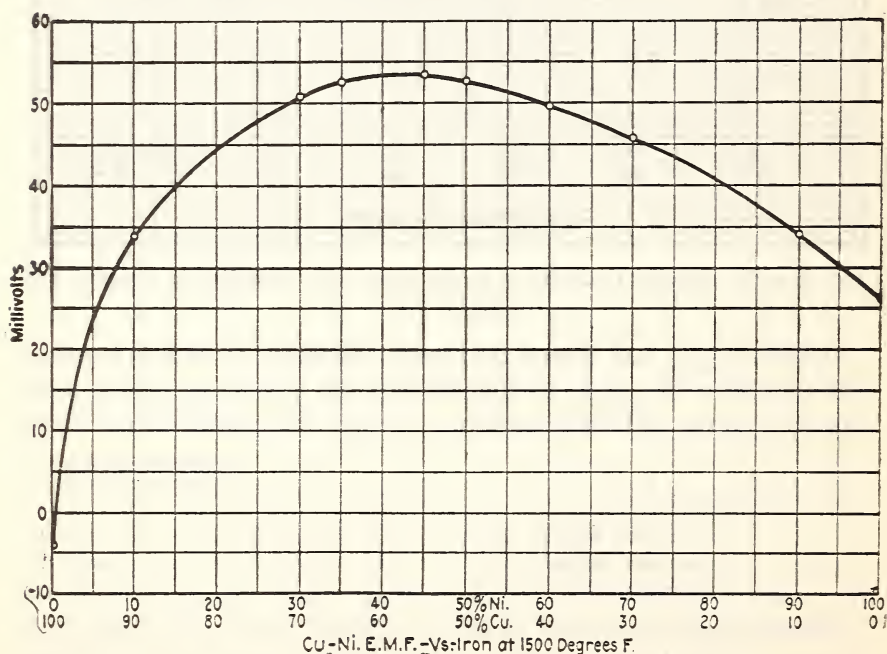
^a Values quoted by Hiorns (254).^c Elongation in 2 inches.^b Values supplied by an American manufacturer.

FIG. 17.—The thermo-electromotive force of copper-nickel alloys toward iron; Bash (537)

The alloys containing less than 60 per cent of nickel are not perceptibly magnetic, but above that percentage of nickel the magnetism of the alloys may readily be detected with a small magnet.

There are several compositions of copper-nickel alloys now in common commercial use. The most prominent ones are the following:

(1) Two and one-half per cent (2.5 per cent of nickel) cupronickel for driving bands of shells.

(2) Fifteen per cent cupronickel, used largely for bullet jackets and by the United States Navy for condenser tubes and feed-water heaters, containing from 14 to 16 per cent of nickel.

(3) Nickel-bronze, or coinage bronze, used for baser currency and containing 25 per cent of nickel.

(4) Copper-nickel, containing 50 per cent of nickel, used for remelting in the manufacture of nickel-copper alloys.

(5) Constantan, used as one element in the construction of thermocouple pyrometers and also as electrical-resistance wire, containing 45 per cent of nickel. (See pp. 55 and 71.)

Of these perhaps the most interesting, in view of its large use during the war, is the bullet-jacket composition commonly known as cupronickel. This alloy is generally made by melting copper in crucibles together with shot or electrolytic nickel, following the practice in melting brass and bronze. The metal has a strong affinity for gases and oxygen and before casting is usually deoxidized with from 0.5 to 1.0 per cent of cupromanganese in order to secure a sound ingot; it may also be readily deoxidized with magnesium. These ingots are cold-rolled to the size required and annealed at about 700° C.

A striking property of this composition is its great malleability, as evidenced by the fact that a cast bar 1.25 inches thick may be cold-rolled to 0.040 inch, or thinner, without intermediate annealing. Webster (481) has determined the effect of cold reductions upon the tensile properties of cupronickel.

TABLE 31.—Effect of Cold Rolling Upon the Tensile Properties of Cupronickel

Reduction in cross section, per cent	Tensile strength	Elongation in 4 inches	Reduction of area
	Lbs./in. ²	Per cent	Per cent
Normalized.....	50 000	28	63
20.....	60 000	5	58
40.....	70 000	3	56
60.....	80 000	2	53

A typical analysis and tensile test of this metal are the following:

Copper (per cent).....	85.16
Iron (per cent).....	.23
Manganese (per cent).....	.11
Carbon (per cent).....	.029
Nickel (difference) (per cent).....	14.47
Tensile strength after cold-rolling to 0.040 inch and annealing (in pounds per square inch).....	46 900
Yield point (per cent).....	22 300
Elongation in 2 inches (per cent).....	35.4

Alloys of this composition are also quite resistant to corrosion and are therefore in wide use as Benedict metal for condenser tubes. (See U. S. Navy Department specifications 46N1a of 1917.) The following values of the tensile properties are typical for this material in the form of tubes.

TABLE 32.—Tensile Properties of Benedict Metal Tubes

Outside diameter	Wall thickness	Tensile strength	Elongation in 10 inches	Remarks
Inch	Inch	Lbs./in. ²	Per cent	
0.517	0.038	43 080	39.0	Annealed.
.516	.036	51 520	8.1	Light drawn.
.750	.047	60 300	a 4.2	Medium drawn.
.750	.047	75 800	a 2.0	Hard drawn.

a In 8 inches.

Bengough (325) has studied the effect of high temperatures on the tensile properties of a 20 per cent copper-nickel alloy.

This metal is subject to a curious type of intercrystalline brittleness at present insufficiently understood. After annealing it frequently is so brittle that it will bend only a few degrees. Under the microscope it presents the appearance shown in Fig. 19, whereas normal annealed cupronickel has a structure shown in Fig. 18, consisting of an aggregate of grains of copper-nickel solid solution. The intercrystalline appearance in the embrittled metal is rather similar to that which occurs on "burning" nickel and Monel metal described above. By some (see Thompson and Barclay, 304) this brittleness is considered as being associated with the precipitation of graphitic carbon, and on this account manufacturers of this metal aim to keep the percentage of total carbon below about 0.04 per cent. It may be noted that 15 per cent cupronickel may be etched and with pleasing results in a solution containing—

- 20 per cent conc. HNO_3 .
- 40 per cent glacial acetic acid.
- 40 per cent acetone.

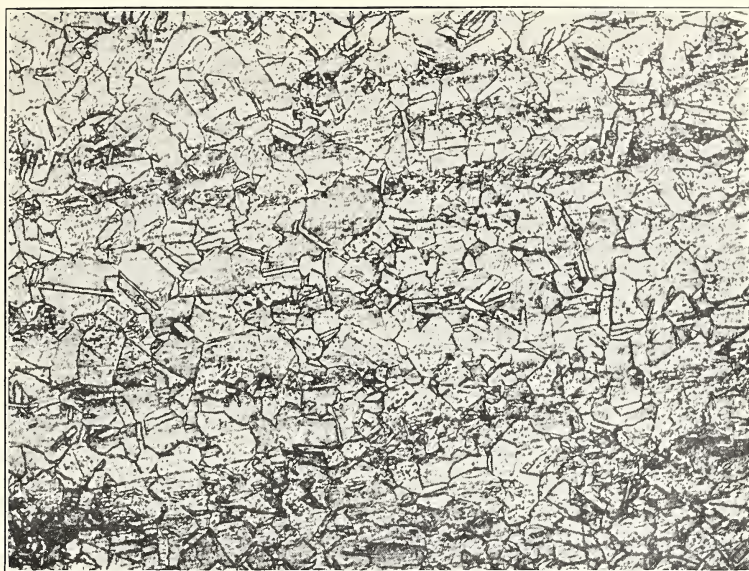


FIG. 18.—Microstructure of normal annealed cupronickel sheet. Etched with 20 per cent nitric acid, 40 per cent acetic acid, 40 per cent acetone. $\times 150$

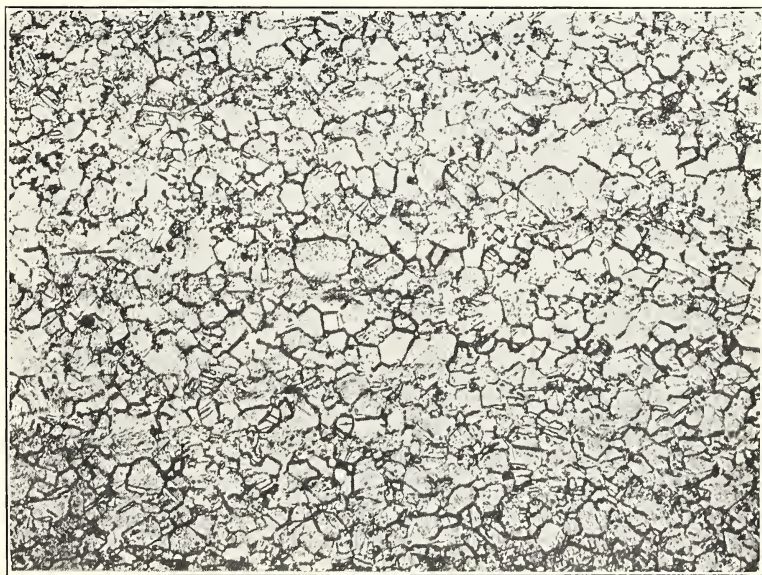


FIG. 19.—Microstructure of brittle cupronickel sheet showing intercrystalline alteration. Etched in the same manner as Fig. 18. $\times 150$

The cupronickel alloys are found not to be subject to corrosion, or season cracking as are the brasses, bronzes, and also the nickel-silver alloys.

The composition used for "nickel" coinage—that is, containing 25 per cent of nickel—is a very old one. This material has essentially the color of pure nickel, is hard and resistant to abrasion and corrosion; being softer than pure nickel it is not so difficult to stamp as is the latter. It is manufactured in much the same manner as cupronickel. It is estimated that the total amount of nickel used in nickel coinage is not over 15 000 tons.

The alloy, constantan, or copper-nickel, which also is sold under a number of trade names (see Table 47), is chiefly used for pyrometer and electrical resistance wire. It is generally made in a hearth furnace and cast into ingots which are first hot-rolled to wire rod and then cold-drawn with intermediate annealing into wire. It may be rolled at the temperatures (1175 to 1200° C) used for Monel metal and annealed at a slightly lower temperature; that is, 850° C. The tensile properties of copper-nickel alloys containing approximately 45 per cent of nickel will average as follows:

TABLE 33.—Tensile Properties of the 45 per cent Copper-Nickel Alloys

Tensile property	$\frac{1}{4}$ -inch hot-rolled wire rod	Annealed wire	Hard-drawn wire
Tensile strength (pounds per square inch)	65 000-85 000	60 000-65 000	110 000-140 000
Elongation in 2 inches (per cent)	25-40	.....	.....

The values of the electrical properties of these compositions are given in Table 47.

3. COPPER-NICKEL-ZINC ALLOYS; NICKEL SILVER (NICKELENE)⁹

This series of alloys is also of very old origin, having been known in China under the name of packfong, or white copper. The most common name for them at one time was German silver, but since the war the trade has accustomed itself to the term nickel silver. The compositions of this series of alloys which are in commercial use are quite numerous; they will vary usually within the following limits:

	Per cent
Copper	52-80
Zinc	10-35
Nickel	5-30

⁹ The name recently suggested by the nonferrous nomenclature committee of the American Society for Testing Materials.

Nickel silver is marketed in several grades, depending chiefly on the nickel content, high-grade alloys containing about 20 per cent and low-grade ones less than 10 per cent. Abroad these are called firsts, seconds, thirds, fifths, etc., but in this country are named according to their nickel content. An idea of the various names which have been given to these alloys may be obtained from Table 34.

TABLE 34.—Some Names and Compositions of Nickel Silver

Alloy	Percentages of chief components			Percentages of other components
	Cu	Ni	Zn	
Extra white metal.....	50	30	20	
White metal.....	54	24	22	
Arguzoid.....	48.5	20.5	31	
Best best.....	50	21	29	
Firsts or best.....	56	16	28	
Special firsts.....	56	17	27	
Seconds.....	62	14	24	
Thirds.....	56	12	32	
Special thirds.....	56.5	11	32.5	
Fourths.....	55	10	35	
Fifths, for plated goods.....	57	7	36	
Alfenide.....	50-70	10-20	5-30	
Alpakka.....	65.2	13	19.5	
Amberoid.....				
Argentan.....	50-70	10-20	5-30	
Argentan solder.....	35	8	57	
Argentin.....				
Argiroid.....				
Argozoil.....	54	14	28	Sn 2, Pb 2, ornamental casting.
Arguzoid.....	55.78	13.45	23.2	Sn 4.03, Pb 3.54.
Arguzoid.....	48.5	20.5	31	
Argyrolith.....	50-70	10-20	5-30	
Aterite.....	55-60	12-18	13-20	Pb 1-2.5, Fe 6-10.
Carbondale silver.....	66	18	16	
Colorado silver.....	57	25	18	
China silver.....	50-70	10-20	5-30	
Craig gold.....	80	10	10	
Electroplate.....	50-70	10-20	5-30	
Electrum.....	51.5	26	22.5	
German silver.....				
Keens alloy.....				
Lutecin.....				
Maillechort ^a	66.2	16.4	13.4	Pb 0.15, Fe 3.2, Sn 0.22. French analysis.
Markus alloy.....				
Neogen.....	58	12	27	Sn 2, Al 0.5.
Nevada silver.....				
New silver.....				
Nickelin.....	68-55	31-32	0-13	For resistance wire.

^a French generic name for this type of alloy; analysis given is of particular sample and is not necessarily general.

TABLE 34.—Some Names and Compositions of Nickel Silver—Continued

Alloy	Percentages of chief components			Percentages of other components
	Cu	Ni	Zn	
Nickelin.....	74.5	25	.....	Fe 0.5
Nickel Oreide.....	66-87	5-10	0-10	
Platinoid.....	54.04	24.77	20.42	Fe 0.5, Mn 0.5.
Platinoid.....	60	14	24	W 1-2.
Popes Island metal ^a	70	14	15	
Potosi Silver.....				
Ruelz alloys.....				
Spoon metal.....				
Silveroid.....				
Silverite.....				
Silverine.....				
Sterline.....	68	17-18	13-14	Fe 0.5-.75.
Sterlin.....	68.5	17.88	12.84	Pb 0.76.
Suhler white copper.....	40.4	31.6	25.4	Sn 2.6 Co 0.5-.6.
Tutenay.....	45.7	17.3	37	
Victor metal.....				
Virginia silver.....				
Weiss Kupfer.....				
White metal.....				
White copper.....				
Weiss Kupfer.....				
Wessells silver.....	51-65	19-32	12-17	Ag 2, FeO 0.5

^a French generic name for this type of alloy; analysis given is of particular sample and is not necessarily general.

These alloys are largely used as substitutes for silver and as base metals for plated silverware of all sorts, their suitability for both purposes being due to the fact that their color is very similar to that of silver. They are used in the production of a large number of ornamental and other fittings and stampings for which an attractive finish and resistance to corrosion is desired and also in the form of wire for small springs and for electrical purposes. (See p. 71.) Their color varies from a nearly white, nickel color with the higher percentages of nickel to a yellowish-white color in the compositions of lower grade or nickel content.

The compositions of nickel-silver used for any specific purpose are quite variable; there are given below in Table 35 both typical compositions and ranges of compositions for different classes of service. It will be noted that lead is added when ready machinability is desired (key stock); it is kept out, however, in material which is to be spun or drawn, as it diminishes the ductility of the alloy.

TABLE 35.—Percentage Compositions of Nickel Silver in Commercial Use

Material	Nickel	Copper	Zinc	Lead
Cutlery and knife stock	15-25	55-65	14-20	Fe 0.5-1.5
Key stock	8-18	55-65	15-35	1-2
Jewelers' wire	5-25	53-63	25-32	.....
Brazing solder	8-20	35-40	40-55	.....
Watchcase metal	10-28	55-65	16-30	0-1
Spoon and fork stock	10-20	57-66	20-30	.....
Platers' bars and cores	5-25	56-70	18-24	.....

TYPICAL COMPOSITIONS USED IN AMERICAN MANUFACTURED PRODUCTS

30 per cent.	30	46.67	23.33	.....
25 per cent.	25	50	25	.....
Spoon stock	20	60	20	.....
20 per cent.	20	53.33	26.67	.....
Spoon stock	18	65	17	.....
18 per cent.	18	72	10	.....
Bolster silver	18	65.50	16	0.50
Spring silver	18	54.67	27.33	.....
Spinning silver	17.50	67	15.50	.....
Spinning silver	16	67	17	.....
Bolster silver	16	56	28	.....
15 per cent.	15	60	25	.....
15 per cent.	15	56.67	28.33	.....
12 per cent.	12	58.67	29.33	.....
Spinning silver	12	66	22	.....
Key stock	12	60	26	2.0
Key stock	12	65	22	1.0
10 per cent.	10	62	28	.....
10 per cent.	10	60	30	.....
8 per cent.	8	61.33	30.67	.....
5 per cent.	5	72	23	.....
5 per cent.	5	63.33	31.67	.....

Results of analyses of two typical compositions of nickel silver follow:

TABLE 35.—Typical Compositions of Nickel Silver

Metal	No. 1	No. 2
	Per cent	Per cent
Copper	63.03	63.39
Lead	None	None
Iron	.12	.13
Manganese	.037	.....
Nickel	16.69	18.37
Zinc	Remainder	17.98

The alloys are produced by melting copper together with nickel-silver scrap in graphite crucibles, adding the nickel and zinc, deoxidizing with from one-fourth to one-half of 1 per cent of

cupromanganese and pouring into ingots, which are cold-rolled, with annealing and pickling, into the sheet or strip required or drawn into wire. The presence of zinc renders this alloy much easier to cast in a sound condition than cupronickel. Annealing is carried out usually at 700° C in a muffle furnace, to exclude air.

Copper, zinc, and nickel in the proportions used in nickel silvers unite to form a solid solution; these alloys are therefore similar structurally to high and low brass, or to copper-nickel alloys and consist of one (alpha) constituent only. They may be etched with ammonium hydroxide and hydrogen peroxide in the manner used for high brass.

An idea of the tensile properties of the copper-nickel-zinc alloys may be obtained from Table 37, which gives some typical values for commercial material:

TABLE 37.—Tensile Properties of Copper-Nickel-Zinc Alloys

Form	Tensile strength	Elongation in 2 inches	Percentage composition		
			Nickel	Copper	Zinc
	Lbs./in. ²	Per cent			
Strip, hard	130 000	2	30	47	23
Strip, annealed	73 000	32	30	47	23
Strip, annealed	71 000	38	25	55	20
Strip, hard	94 000	2.5	18	64	18
Strip, annealed	58 000	33	18	64	18
Strip, hard	107 000	2	18	55	27
Strip, annealed	69 000	29	18	55	27
Strip, hard	92 000	4	10	62	28
Strip, annealed	63 000	48	10	62	28

Table 38 gives some very interesting data taken from an article by Price and Davidson (486) on the effect of cold-rolling and annealing on different compositions of nickel-silver strip.

TABLE 38.—Effect of Cold-Rolling and Annealing on the Mechanical Properties of Nickel Silver; Annealing Temperature Ranges (Price and Davidson, 486)

No. of alloy	Chemical composition						Annealing range	Previous reduction
	Cu	Pb	Fe	Ni	Mn	Zn		
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	°C	Per cent
A.....	64.68	Trace	0.194	6.73	0.06	Remainder	300-450	20-60
B.....	65.82	1.27	.227	6.17	.06	Remainder	300-450	20-60
C.....	65.44	Trace	.345	17.83	.08	Remainder	450-600	20-60
D.....	65.60	1.08	.238	17.77	.06	Remainder	450-600	20-60

TABLE 38.—Effect of Cold-Rolling and Annealing on the Mechanical Properties of Nickel Silver; Annealing Temperature Ranges (Price and Davidson, 486)—Con.

No. of alloy	Properties of cold-rolled strip ^a						Properties of annealed strip		
	Yield point ^b	Tensile strength	Elongation in 2 inches	Reduction of area	Brinell hardness ^c	Scleroscope hardness ^d	Tensile strength	Elongation in 2 inches	Scleroscope hardness ^d
	1000 lbs./in.	1000 lbs./in.	Per cent	Per cent			1000 lbs./in.	Per cent	
A ^e	80-110	80-110	2-6	25-45	140-175	30-50	50-65	50-65	12-17
B ^e	80-110	80-110	2-7	18-45	145-175	35-50	50-60	50-60	12-17
C ^f	85-100	85-100	2-4	20-45	160-175	30-45	55-65	35-40	12-17
D ^f	85-100	85-100	1-4	20-40	160-175	35-45	55-60	30-35	12-17

^a The values are for reductions of from 35 to 75 per cent, respectively.

^b Load producing set of 0.01 in 2 inches; that is, one-half of 1 per cent.

^c 10 mm ball, 500 kg.

^d Universal hammer.

^e The annealed values are for metal annealed at from 500-650° C after cold reductions of from 20 to 60 per cent.

^f The annealed values are for metal annealed at from 600-750° C after cold reductions of from 20 to 60 per cent.

4. FERRONICKEL ALLOYS

The alloys of nickel with iron, including nickel steels, are by far the commercially most important alloys of this metal, and the range of compositions used is a very wide one—from the alloys of low nickel content, the nickel steels, to those containing 30 per cent and more of nickel. These alloys were first discovered in the composition of meteorites and have since not ceased to interest and puzzle investigators because of the unusual properties of the alloys containing from 5 to 40 per cent of nickel.

Binary alloys of all compositions solidify as solid solutions which upon cooling suffer both phase and magnetic transformations of great scientific interest and technical importance. The constitution diagram of the alloys of nickel and iron is given in Fig. 20. Without entering upon a detailed discussion of the constitution of these alloys for which further references (522, 523) should be consulted, it is observed that the addition of nickel to iron and steel immediately depresses the temperature of both the A_2 and A_3 transformation and in addition increases the temperature difference or lag between Ac_2 and Ar_2 ; that is, the temperatures at which iron loses its magnetism upon heating and regains it upon cooling, respectively. This temperature range, between Ac_2 and Ar_2 , within which the alloy may be either magnetic or nonmagnetic, depending on whether it has been heated or cooled to that range, is widened from practically zero for pure iron to about 500° C for an alloy containing 25 per cent of nickel; at the same time the magnetic transformation range is lowered

to ordinary temperatures and below. With increasing nickel content the temperature range of magnetic transformation again rises and becomes quite narrow; that is, there is little lag in the transformation on heating and cooling. Steels of the former group, containing from 3 to about 30 per cent nickel have become known as irreversible steels, whereas those of higher nickel content are called reversible ones. Accompanying these magnetic changes

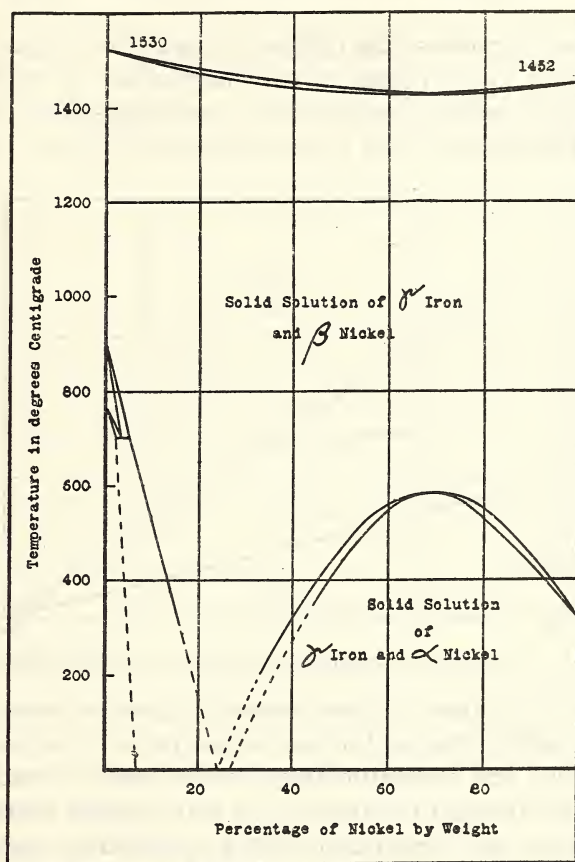


FIG. 20.—Equilibrium diagram of iron-nickel alloys according to Guertler (259)

which characterize reversible and irreversible steels are corresponding ones in other properties, such as thermal expansivity, elasticity, electrical resistivity, the thermal alterations of which are also reversible or irreversible depending on the composition.

The presence of carbon causes further complications in the properties and behavior of these alloys and will be considered only in connection with the nickel steels of low nickel content.

(a) NICKEL STEELS

Nickel steel was the fourth alloy steel to be introduced and was first described in some detail by James Riley (530). The general subject of nickel steels is too broad for anything but the merest mention in this place, and references should be consulted for further details.

The principal effects of the addition of nickel to steel are the following:

(1) Nickel depresses the critical temperature ranges of steel, and according to the degree of such depression we may consider three groups of nickel steels—namely, pearlitic steels, which have normal transformation and heat treatment or critical ranges and

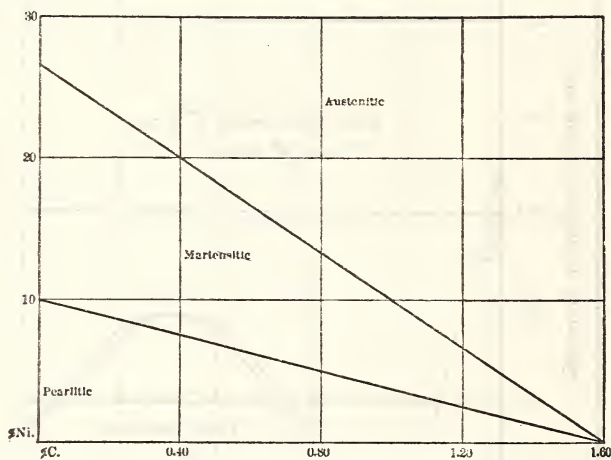


FIG. 21.—Structural classification of nickel steels according to Guillet

are similar to ordinary carbon steels in a general sense; martensitic steels, self-hardening but too brittle to be of any importance commercially; and austenitic steels, which are not susceptible to hardening by thermal treatment, and may perhaps more properly be considered as ferronickel alloys containing carbon. The nickel and carbon content of the steel determine its inclusion in any one of the above groups. Fig. 21 according to Guillet gives a classification of different compositions of nickel steels.

(2) Nickel dissolves in the ferrite of steel and increases the hardness and strength without a corresponding loss of ductility. Thus Bullens (516) states that the addition of each 1 per cent (up to 5 per cent) of nickel to steel of forging grades will, without loss of ductility, increase the tensile strength and yield point from 4000 to 6000 pounds per square inch, in the natural or unheat-treated

condition. But it is in the heat-treated condition that the superiority of steels containing nickel is most evident and of most commercial importance. This is illustrated from the following data, Table 39, collected by the Society of Automobile Engineers, showing a comparison between the tensile properties of a 0.40 per cent carbon steel without nickel and the same with 3.5 per cent of nickel in the heat-treated condition.

TABLE 39.—Comparison of Tensile Properties of a 0.40 Per Cent Carbon Steel With and Without Nickel

Material	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area
	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
0.40 per cent carbon steel.....	53 000	90 000	25	62.5
0.40 per cent carbon, 3.5 per cent nickel steel.....	83 000	108 000	25	66

(3) Nickel exerts an influence on the grain size of ferrite and pearlite, tending to produce a finer grain structure and finer pearlite, shading into sorbite. In the same sense it diminishes the rate of grain growth within the heat treatment temperature ranges and thus minimizes the danger of overheating during heat treatment.

(4) The structural effects of nickel noted above make a nickel steel (2–3.5 per cent Ni, 0.10–.20 per cent C) invaluable for case-hardening and superior to carbon steels in (a) uniformity of zone of carburization and (b) in mechanical properties of the core after heat treatment.

The beneficial effects of nickel upon steel are intensified by the presence of other elements, particularly chromium, and chromium-nickel steels are perhaps more widely used to-day for heat-treated forgings for automobiles and other construction than are the straight nickel steels.

The following grades of steel are in most common commercial use:

(a) STRUCTURAL 3½ PER CENT NICKEL STEEL.—This is the oldest and best known composition of nickel steel and constitutes the bulk of commercial nickel steel produced to-day. Its composition will average:

	Per cent.
Nickel.....	3.0–3.5
Carbon.....	.20–.40

It is usually made in the open-hearth furnace and is used both in the rolled or forged condition and after heat treatment.

In the former condition it is much used for structural shapes in construction of bridges and similar structures. It has also been used in the form of rails, although the advantage in point of economy of it for this purpose over carbon steel has not been satisfactorily demonstrated. In the heat-treated condition it is used for gun, engine and locomotive forgings, as well as for many automobile parts of which the service is too severe for ordinary carbon steels. The average physical properties of this

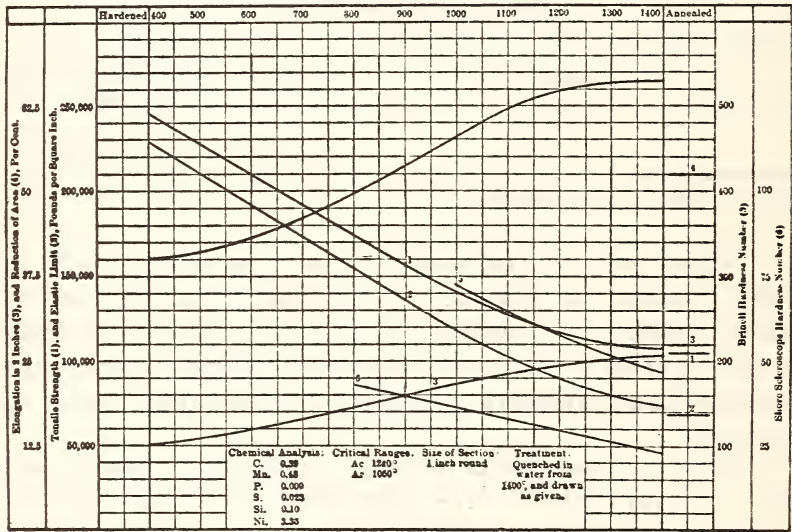


FIG. 22.—Mechanical properties of 3½ per cent heat-treated nickel steel; Society of Automotive Engineers, (Bullens, 516)

composition of steel in the heat-treated condition are shown in Fig. 22.

(b) NICKEL-CHROMIUM STEELS FOR HEAT-TREATED AUTOMOBILE AND OTHER FORGINGS.—These compositions constitute the most prominent group of “automobile” steels and are used for a great variety of parts and construction where high strength, toughness, and ductility are required.

TABLE 40.—Typical Ranges of Composition of Nickel-Chromium Steels

Kind	Chromium	Nickel	Carbon
	Per cent	Per cent	Per cent
Low.....	0.5	1.5	0.20-.50
Medium.....	0.5-1.5	1.5-3.5	.20-.50
High.....	1.5	3.5	.40-.50

The "low" and "medium" nickel-chromium steels are used primarily in the automobile industry for crank shafts, axles, driving shafts, spindles, bolts, etc., and for casehardened pivot pins, and cam rollers. The "high" nickel-chromium steels are used in the manufacture of heat-treated gears. The latter compositions are the principal ones used also in the manufacture of both armor plate and of armor-piercing projectiles. The physical

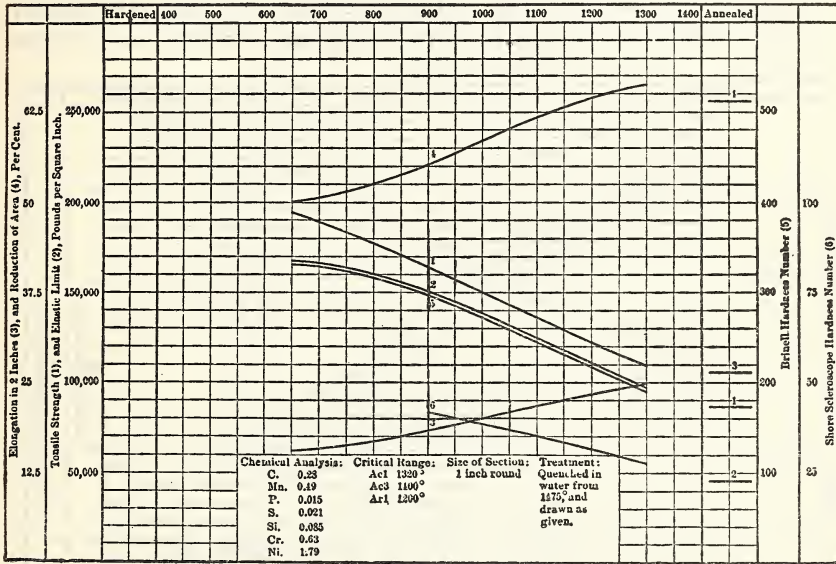


FIG. 23.—Mechanical properties of heat-treated "low" nickel-chromium steel; Society of Automotive Engineers, (Bullens, 516)

properties of typical compositions of these steels are given in Figs. 23 and 24 in the heat-treated condition.

(c) NICKEL STEEL FOR CASEHARDENING.—The principal properties of nickel steel which make it invaluable for casehardening are noted above under (4); in addition there exists the possibility in the case of high nickel steels (nickel, 5 to 7 per cent) of obtaining an air or self-hardening casehardened surface layer together with a tough pearlitic core. Typical compositions used for casehardening are given below:

Nickel.....	1.5 - 3.5	} Low nickel
Carbon.....	.10 - .20	
Nickel.....	5-7	} High nickel
Carbon.....	10-15	

(d) MAYARI STEEL FROM CUBAN ORES.—This is a natural alloy produced in the blast furnace and open-hearth furnace; it has

been used principally in the form of rails and track bolts. Its composition averages:

	Per cent
Nickel.....	1.0-1.5
Chromium.....	.20-.70

(e) HIGH-NICKEL STEELS—These are perhaps more properly ferronickel alloys.

	Per cent
Nickel.....	25-40
Carbon.....	.3-.5

These alloys are austenitic and not subject to heat treatment; they are, however, naturally quite tough and strong, have a low

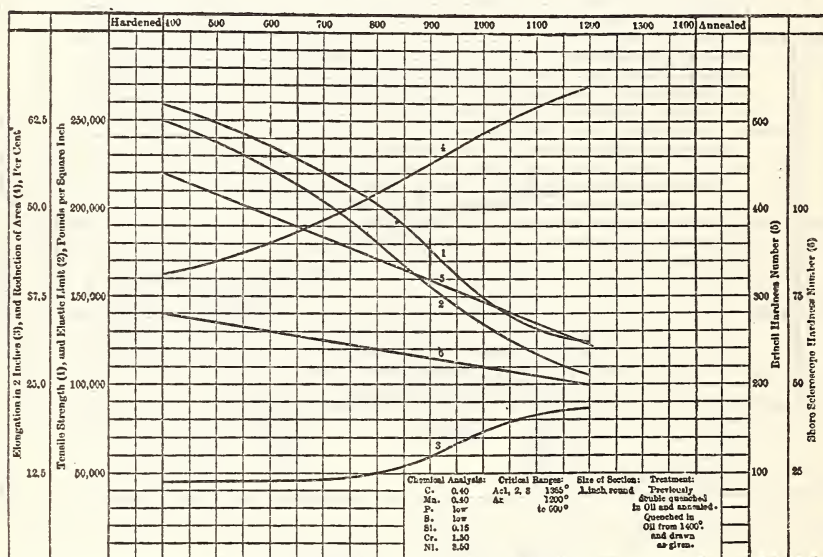


FIG. 24.—Mechanical properties of heat-treated "high" nickel-chromium steels; Society of Automotive Engineers, (Bullens, 516)

thermal expansivity and are very resistant to corrosion in air, fresh or sea water. They are much used for gas engines, valves, and spindles, for ignition and boiler tubes, for valve stems on sea-water pumps. The alloys may be rolled and forged, but are not so readily machined as ordinary steel. They will have the following average tensile properties in the natural, unheat-treated state:

TABLE 41.—Tensile Properties of High-Nickel Steels

Tensile properties	Results for 25 to 28 per cent nickel, 0.3 to 0.5 per cent carbon	Results for 30 to 35 per cent nickel	Results for 35 to 38 per cent nickel
Tensile strength.....lbs./in. ² ..	85-92 000	85-95 000	100-115 000
Yield point.....lbs./in. ² ..	35-50 000	40-50 000	64-78 000
Elongation in 2 inches.....per cent..	30-35	30-40	25-35
Reduction of area.....per cent..	50-60	40-60	50

The alloys containing about 25 per cent of nickel are much used for electrical-resistance wire in the construction of rheostats and electrical heaters. Table 42 gives values of the electrical and thermal properties of binary alloys of nickel and iron.

TABLE 42.—Electrical and Thermal Properties of Nickel-Iron Alloys

Nickel, per cent	Electrical resistivity ^a (Burgess and Aston (365))	Specific resistance, 20° C (L. R. Ingersoll and others ^b)	Temperature coefficient of resistance, 0-100° C (L. R. Ingersoll and others ^b)	Thermal conductivity, 20-100° C (L. R. Ingersoll and others ^b)	Thermoelectric power (against copper) 0-96° C (L. R. Ingersoll and others ^b)	Mean coefficient of resistivity between 0° and t°C (Guillaume (527))
	microhm-cm	microhm-cm		cgs units	microvolts/°C	
0.....	12.1	.....	.....	0.1428	.....	.....
0.27.....	13.1	.....	.....	.....	.....	.....
0.56.....	15.4	.....	.....	.....	.....	.....
1.07.....	15.9	.....	.....	.1035	.....	.....
1.93.....	16.4	.....	.....	.1009	.....	.....
4.0.....	.....	20.9	0.0020	.....	2.32	.....
7.0.....	.....	25.2	.0023	.....	7.32	.....
7.05.....	26.9	.....	.....	.0727	.....	.....
8.17.....	26.7	.....	.....	.....	.....	.....
10.20.....	28.6	.....	.....	.0687	.....	.....
11.29.....	29.4	.....	.....	.....	.....	.....
12.07.....	30.3	.....	.....	.....	.....	.....
13.0.....	.....	33.0	.0018	.....	16.9	.....
13.11 ^c	34.8	.....	.....	.0534	.....	.....
14.0.....	.....	33.9	.0016	.....	17.2	.....
18.0.....	.....	35.9	.00084	.....	21.0	.....
19.21.....	36.2	.....	.....	.0502	.....	.....
21.0.....	.....	38.8	.0018	.....	23.5	.....
22.0+3 Cr.....	.....	.....	.....	.....	.....	(784-0.13t) 10 ⁻⁶
22.11.....	38.7	40.0	.0018	.0490	21.0	.....
25.20.....	63.2	.....	.....	.0320	.....	.....
26.2.....	.....	.....	.....	.....	.....	(844+0.01t) 10 ⁻⁶
26.40.....	65.5	35.9	.0016	.....	16.7	.....
28.42.....	82.0	.....	.....	.0278	.....	.....
28.7.....	.....	.....	.....	.....	.....	(700-0.20t) 10 ⁻⁶
30.4.....	.....	.....	.....	.....	.....	(897-0.43t) 10 ⁻⁶
35.0.....	.....	.....	.....	.....	.....	(1561-1.69t) 10 ⁻¹
35.09.....	81.1	92.0	.0011	.0262	9.79	.....
35.7.....	.....	.....	.....	.....	.....	(1161-1.68t) 10 ⁻⁶
40.0.....	.....	74.1	.0022	.....	22.4	.....
45.0.....	.....	.....	.....	.....	29.0	.....
47.08.....	44.7	47.5	.0036	.0367	31.9	.....
75.06.....	22.1	.....	.....	.0691	.....	.....
90.0.....	.....	15.5	.0034	.....	17.9	.....
100.00.....	12.4	.....	.....	.1402	.....	.....

^a Alloys produced in magnesia crucible from electrolytic iron and electrolytic nickel; carbon less than 0.10 per cent.

^b The Physical Review, 16, p. 126; alloys are the same as those used by Burgess and Aston, see footnote ^a.

^c Contains 0.888 per cent carbon.

See also section X, 5 on "Alloys for electrical purposes" for further information on this application of the ferronickel alloys.

Within the range of compositions from 20 to 30 per cent nickel, the ferronickel alloys may readily be obtained in a nonmagnetic condition by cooling at normal rates from rolling or forging temperatures. They are used in this condition for the production of nonmagnetic parts requiring strength and toughness. Table 43 gives some values of the magnetic properties of ferronickel alloys. Information concerning the effect of high temperatures on the tensile properties of 30 per cent nickel steel will be found in Table 26.

TABLE 43.—Magnetic Properties of Nickel-Iron Alloys

Nickel, per cent	Hegg, 1910 (364)					Curie constants ^a
	Density, D	Transformation temperatures (Curie points)		Saturation values at 0° absolute		
		Heating	Cooling	Magnetic moment per unit mass	B-H	
	g/cm ³	° C	° C			
0.....	7.875	758	.....	223.2	22 090	0.072
10.....	7.89	730	532	221.0	21 910	.0577
20.....	8.02	625	218	210.8	21 240	.0460
30.....	8.06	533	127	203.6	20 620	.0315
40.....	7.63	365	.....	184.2	17 660	.0251
50.....	8.05	527	.....	169.2	17 120	.0227
60.....	8.29	599	.....	146.8	15 290	.0185
70.....	8.39	613	.....	127.1	13 400	.0157
80.....	8.52	562	.....	103.1	11 040	.0126
90.....	8.60	480	.....	80.6	8 710	.0100
100.....	8.86	374	.....	58.8	6 550	.0056

^a Weiss and Foex, 9111.

More recently Yensen (352) has made a thorough study of the electrical and magnetic properties of iron-nickel alloys prepared by melting in vacuo. In Figs. 25 and 26 are reproduced some of his typical results. He finds that the alloys containing approximately 50 per cent of nickel can be forged and worked and that they have the following average electrical and magnetic properties which may be compared with those of pure iron and nickel:

Metal	Flux density <i>H</i> = 100 gauss	Saturation value	Hysteresis loss <i>B</i> = 10000 ergs/cm/cycle	Electrical resistivity
		gausses		microhm-cm
Pure iron.....	18 500	22 500	1 100	11
50 per cent alloy.....	15 500	15 500	800	45
Pure nickel.....	6 000	6 000	25 000	8

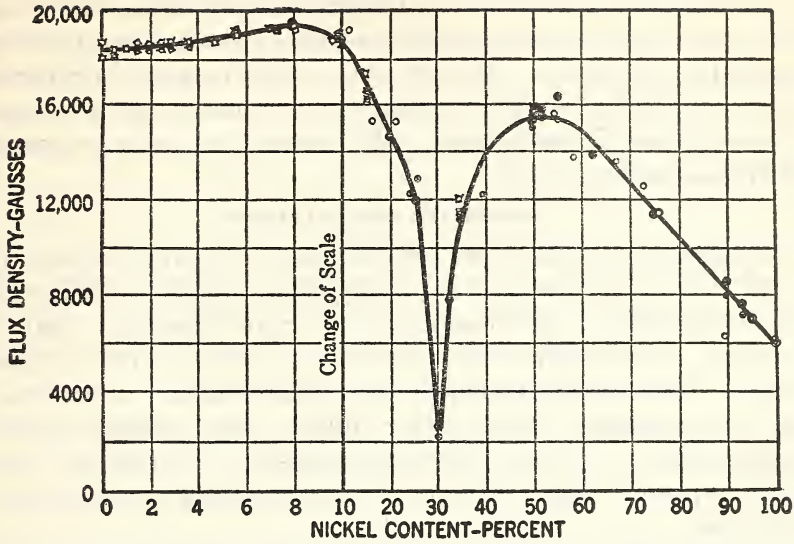


FIG. 25.—The magnetic permeability of iron-nickel alloys melted and annealed in vacuo for H equals 100 (Yensen 352)

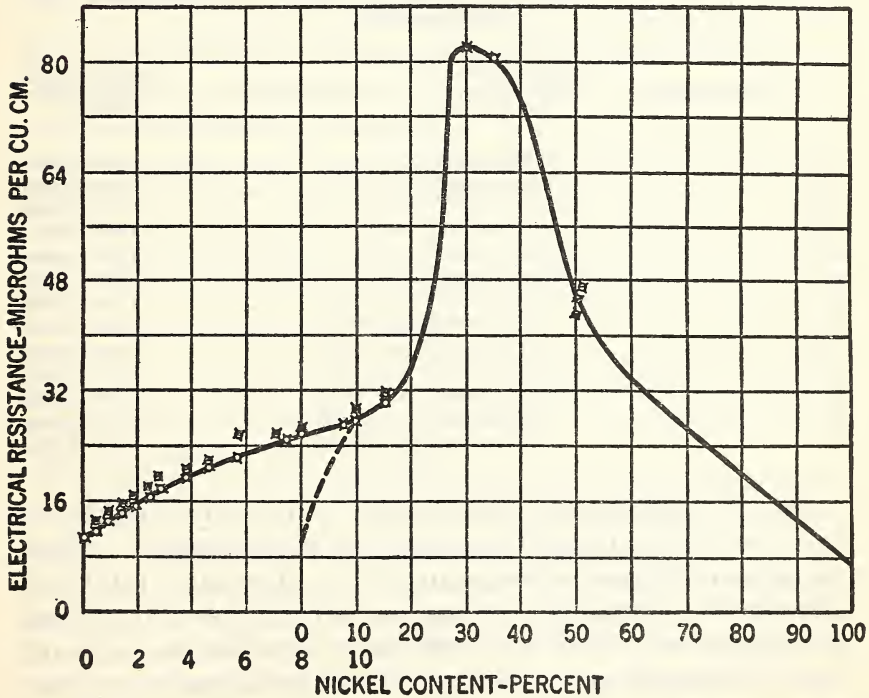


FIG. 26.—The electrical resistivity of iron-nickel alloys melted and annealed in vacuo (Yensen, 352)

As the 50 per cent alloys are relatively incorrodible, they should be of value under special conditions in the construction of electromagnetic equipment. Another interesting magnetic characteristic of this alloy is the fact that the B - H curve up to $B = 2000$ to 4000 gauss is nearly linear, which makes it of value for certain electromagnetic meters.

(b) INVAR AND RELATED ALLOYS

Beginning at about 25 per cent of nickel the thermal expansivity of the ferronickel alloys at 20° C diminishes rapidly with increasing nickel content up to about 34 per cent; thereafter again increasing, first rapidly and then more slowly, to that of pure nickel. These curious changes are utilized in the manufacture of three patented alloys—*invar*, *dilver*, and *platinite*—having respectively a very low thermal expansivity at ordinary temperature, and values of it nearly equal to those of glass and of platinum.

Table 44 gives values of the thermal expansivity of ferronickel alloys.

TABLE 44.—Thermal Expansivity of Nickel-Iron Alloys Between 0 and 38° C
(Guillaume, 527)

Nickel, per cent	Mean coefficients of linear expan- sions $\times 10^6$	Nickel, per cent	Mean coefficients of linear expan- sions $\times 10^6$
0.....	10.354+0.00523 $\frac{1}{2}$	44.4.....	8.506-0.00251 $\frac{1}{2}$
5.0.....	10.529+0.00580 $\frac{1}{2}$	48.7.....	9.901-0.00067 $\frac{1}{2}$
19.0.....	11.427+0.00362 $\frac{1}{2}$	50.7.....	9.824+0.00243 $\frac{1}{2}$
26.2.....	13.103+0.02123 $\frac{1}{2}$	53.2.....	10.045+0.00031 $\frac{1}{2}$
27.9.....	11.288+0.02889 $\frac{1}{2}$	70.3.....	11.890+0.00387 $\frac{1}{2}$
28.7.....	10.387+0.03004 $\frac{1}{2}$	100.0.....	12.661+0.00550 $\frac{1}{2}$
30.4.....	4.570+0.01194 $\frac{1}{2}$	12.2+1 Cr.....	11.714+0.00508 $\frac{1}{2}$
31.4.....	3.395+0.00885 $\frac{1}{2}$	16.8+1 Cr.....	11.436+0.00170 $\frac{1}{2}$
34.6.....	1.373+0.00237 $\frac{1}{2}$	16.2+2.5 Cr.....	19.496+0.00432 $\frac{1}{2}$
35.6.....	0.877+0.00127 $\frac{1}{2}$	21.3+3 Cr.....	18.180+0.00426 $\frac{1}{2}$
37.3.....	3.457-0.00647 $\frac{1}{2}$	34.8+1.5 Cr.....	3.580-0.00132 $\frac{1}{2}$
39.4.....	5.357-0.00448 $\frac{1}{2}$	35.7+1.7 Cr.....	3.373+0.00165 $\frac{1}{2}$
43.6.....	7.992-0.00273 $\frac{1}{2}$	36.4+0.9 Cr.....	4.433-0.00392 $\frac{1}{2}$

The alloy called *invar* contains about 36 per cent of nickel and has a mean linear thermal expansivity of approximately 0.000001 per degree centigrade between 0 and 40° C. It melts at 1425° C, has a density of 8.0 grams per cm³ and an electrical resistivity of about 80 microhm-cm. It is very resistant to corrosion in water and may be immersed in it for days without the appearance of rust spots. *Platinite* is quite similar except that it has a thermal expansivity equal to that of platinum, approximately 0.000009

per °C, and contains about 46 per cent of nickel. Dilver has a thermal expansivity coefficient of 0.000008 per °C. Invar as well as the other alloys of similar character and composition may be rolled, drawn, and machined and is used for the manufacture of measuring tapes, length standards, instruments, and chronometers of high accuracy for which temperature-length changes must be almost wholly eliminated. These and similar alloys are produced now in this country. For further information concerning invar, Circular No. 58 of the Bureau of Standards should be consulted. Perhaps the principal present use for platinite is for the sealing-in-wire of electric light bulbs.

5. ALLOYS FOR ELECTRICAL PURPOSES

The chief electrical purposes for which alloys containing nickel are used are for the construction of pyrometer thermocouples, rheostats and electrical heating devices. The use of an alloy containing from 3 to 5 per cent manganese for spark-plug terminals has been mentioned above. The characteristic which renders this group of nickel alloys of value for these purposes is their resistance to oxidation and alteration at the higher temperatures (up to 2000°F) at which they are used, in conjunction with their high electrical resistivity, low-temperature coefficient of electrical resistivity and either high or low thermal electromotive force against iron or copper.

The principal alloys used commercially to-day for base metal thermocouples are copper-constantan, iron-constantan (Leeds and Northrup, Bristol, Brown pyrometers) and Chromel-alumel (the Hoskins thermocouple). The temperature-electromotive force relation of these three elements are given in Tables 45 and 46, the values being average or standard ones. Adams (539) has shown how to apply deviation curves based on one temperature-electromotive force measurement to lots of such wire at slightly different temperature-electromotive force relations. The compositions of these alloys are given in Table 47.

The alloys used for electrical heating and for the construction of rheostats or electrical resistances may be divided into several groups: (1) The nickel-chromium alloys having a high electrical resistivity, low-temperature coefficient together with maximum resistance to oxidation and alteration at higher temperatures; (2) the ferronickel alloys with lower resistivity and resistance to oxidation but considerably cheaper; (3) copper-nickel alloys having lower resistivity and inferior heat-resisting properties than the first class but with practically negligible temperature

coefficient of resistivity at ordinary temperatures, a very necessary property in the construction of precise electrical resistances for measuring instruments, etc.; and (4) the alloys similar to nickel silver which are the oldest alloys used for electrical purposes and are being displaced by the former classes.

The compositions of alloys manufactured commercially to-day are listed in Table 47, together with approximate compositions and physical properties as described principally by the manufacturers. It may be noted that the nickel-chromium alloys are now sold only under license from the Hoskins Manufacturing Co. and the General Electric Co., owners of the Marsh patents; they may be sold only to those having licenses or permission from these owners to use the alloys. Applications for the right to operate under the Marsh patents or for permission to buy the commercial alloys should be addressed to them.

Most of these alloys are furnished in wire and in ribbon form, manufactured by melting either in crucible or electric furnace, pouring into small ingots, which are first hot-rolled and annealed and then cold-drawn with annealing into the finished form.

The general subject of electrical resistance has received much attention by Hunter and Sebast, Sebast and Gray (552, 554). Some of their principal conclusions are here reproduced. An alloy of very high resistivity (113 microhm-cm) and of negligible temperature coefficient (0.000078 per 1° C) was found containing 17 per cent chromium, 71 per cent nickel, and 12 per cent of copper, which would appear to have commercial possibilities; it resists oxidation at higher temperatures to a remarkable degree and is easily manipulated in drawing. An alloy was found containing 48 per cent copper, 39 per cent nickel, and 10 per cent manganese which has a resistivity of 70 microhm-cm and zero temperature coefficient at 20° C; this is superior to manganin in its higher resistivity. The highest values of the resistivity were found in the binary nickel-manganese and nickel chromium and in the ternary ferronickel-manganese, ferronickel-chromium and copper-nickel-chromium alloys. The ternary alloys have a higher value of the resistivity than the binary alloys. Alloys of low temperature coefficient were found chiefly among the copper-nickel-manganese alloys.

An interesting corollary of the development of electrical-resistance alloys for rheostats and heaters has been that of *heat-resisting alloys*, and many compositions used at first because of their electrical and heat or high-temperature resisting properties are now used because of the latter alone. The nickel-chromium

alloys in the form of castings are now much used for furnace muffles, carbonizing and annealing boxes, and pyrometer protection tubes. These alloys (see Table 47) withstand very well the action of gas and oil flames as well as that of molten lead, cyanide, or of carbonizing mixtures at temperatures up to 2000° F (1100° C).

TABLE 45.—Calibration Data of Representative Couples. Cold-Junction Temperature, 0° C (Foote, Harrison, and Fairchild, 540)

[B represents mean calibration by United States Bureau of Standards of iron-constantan couples from all sources. L represents mean calibration of Leeds & Northrup's iron-constantan couple]

Copper-constantan		Iron-constantan			Chromel-alumel	
Emf	Temperature	Emf	Temperature		Emf	Temperature
			B	L		
millivolts	° C	millivolts	° C	° C	millivolts	° C
0	0	0	0	0	0	0
1	25	5	105	95	5	122
2	49	10	204	186	10	243
3	72	15	299	277	15	363
4	94	20	392	367	20	482
5	115	25	483	457	25	601
6	136	30	574	546	30	721
7	156	35	662	632	35	844
8	175	40	749	713	40	970
9	194	45	836	792	45	1100
10	213	50	924	871	.....	.....
11	232	55	1011	950	.....	.....
12	250	60	.....	1030	.....	.....
13	268	.....	.....	.....	.....	.....
14	285	.....	.....	.....	.....	.....
15	302	.....	.....	.....	.....	.....
16	319	.....	.....	.....	.....	.....
17	336	.....	.....	.....	.....	.....
18	353	.....	.....	.....	.....	.....

TABLE 46.—Chromel-Alumel Thermocouple ^a

Temperature		Electro-motive force	Temperature		Electro-motive force
° C	° F		° C	° F	
38	100	1.50	760	1400	31.60
94	200	3.90	815	1500	33.90
149	300	6.22	872	1600	36.20
204	400	8.45	927	1700	38.45
261	500	10.72	984	1800	40.60
316	600	13.00	1038	1900	42.70
371	700	15.25	1092	2000	44.80
427	800	17.60	1150	2100	46.90
482	900	20.00	1205	2200	49.00
538	1000	22.30	1260	2300	51.06
594	1100	24.70	1316	2400	53.05
650	1200	27.00	1371	2500	55.08
705	1300	29.30			

^a Data from Hoskins Mfg. Co.

TABLE 47.—Composition and Properties of Electrical Alloys

[illegible]

Nichloy ϵ_f	Castings	23	20	50	1	$\frac{1}{2}$ Si				1100
Chromax		75	25							
B. Ferronickel										
Alloys:										
Climax a	Wire, ribbon	25		75		83.1	.00098	500	.00054	
No. 193 a	do	30	2	68		87.2	.0007	525	.0004	
Comet c	do	32	3	Bal.		87.0	.0007	525	.00039	
Phenix c	do	25		Bal.		83.1	.0011	500	.00061	
Ferrozoid g						84.0		506		
Kruppin g		28		Bal.		85.0		512		
Vestalin g						85.1		512		
C. Nickel - Cop-										
per Alloys:										
Advance a	Wire, ribbon	44-46		Bal.	0.75- 1.25	48.9	Nil	294		
Ideal c	do	45		55		49.2	.000005	296	.000003	

a These alloys manufactured by the Driver-Harris Co.; these data were taken from their catalogue and from information kindly supplied by this company in a private communication. See also paper by Leon Hart, Nickel chromium alloys; Bull. A. T. M. S.; 1920.

b Specific heat of this alloy = 0.111 cal./gram at 100° C.

Thermal conductivity = .0341 cal./sec./cm.

c These alloys manufactured by the Electrical Alloys Co.; these data were taken from their catalogue and from information kindly supplied by this company in a private communication.

d These alloys manufactured by the Hoskins Manufacturing Co.; these data were taken from their catalogue and from information kindly supplied by this company in a private communication.

e These alloys manufactured by the Hiram Walker & Sons Co.; these data were taken from their catalogue and from information kindly supplied by this company in a private communication.

f Chemical composition includes $\frac{1}{2}$ Al, C, V, in addition to the elements given.

g Data by Law (247).

6. ACID-RESISTING ALLOYS

Many of the nickel alloys display an even greater resistance to acid corrosion than nickel itself. The acid-resisting properties of Monel metal have already been discussed; it is not resistant to the action of nitric acid.

The chromium-nickel alloys are acid resisting and are used for dipping baskets and other articles exposed to acid corrosion. The following results of tests (Table 48) communicated by the Driver-Harris Co. indicate the degree of resistance to acid corrosion afforded by the composition used for nichrome castings.

TABLE 48.—Resistance to Acid Corrosion of Nichrome Castings ^a

Acid	Loss in weight in per cent of weight (125 g) per day			
	20 per cent acid	30 per cent acid	50 per cent acid	60 per cent acid
Sulphuric.....	0.009	0.005	0.005	0.005
Hydrochloric.....	.14	.34	.....	.....
Nitric.....	.08	.13	.22	.30

^a Samples (125 g weight) immersed in cold acid (300 cc) for 200 hours.

Prof. S. W. Parr (569) has developed an alloy which he calls Ilium, of the following composition:

	Per cent		Per cent
Copper.....	6.42	Aluminum.....	1.09
Manganese.....	.98	Iron.....	0.76
Silicon.....	1.04	Chromium.....	21.07
Tungsten.....	2.13	Molybdenum.....	4.67
Nickel.....	60.65		

This alloy has been applied by him with success in the construction of combustion chambers of calorimeters as it is practically unattacked by 25 per cent nitric acid. The alloy may be cast and machined, although with some difficulty; it has a tensile strength of about 50 000 pounds per square inch.

Tungsten-nickel alloys have been prepared by Irmann (567) and their resistance to the action of sulphuric acid studied. He discovered that the resistance of nickel to the action of 65 per cent acid, which itself is considerable, is increased fourfold by the addition of 5 per cent of tungsten and twelvefold by the addition of 10 per cent. Alloys containing under 18 per cent have sufficient ductility that they may be formed into sheets.

Fairlie (570) has reported some tests of nickel-lead alloys for acid-resisting purposes. Alloys containing from 1 to 3 per cent of nickel and balance lead, were more resistant to the action of 50 to 60° B sulphuric acid, both hot and cold, than pure lead and had a tensile strength of about 3000 pounds per square inch, about 30 per cent greater than that of lead. The antimony-lead alloys were much harder and stronger, and although resistant to the action of cold acid, were not resistant to the action of hot acid. Some of his results are reproduced in Table 49 below.

TABLE 49.—Acid Resistance of Nickel-Lead Alloys (Fairlie, 570)

Composition	Elonga- tion in 0.5 inch	Tensile strength	Loss in weight in 50 Be H ₂ SO ₄		Loss in weight in 50 Be H ₂ SO ₄	
			Cold; loss in 1 week	Hot (184° C) loss in 1 week	Cold; loss in 1 week	Hot (184° C) loss in 1 week
	Per cent	Lbs./in. ²	Per cent	Per cent	Per cent	Per cent
100 per cent Pb.....	110	2360	0.014	0.357	0.078	0.419
80 per cent Pb, 20 per cent Sb.....	5	7540	.015	2.425	.091	5.817
99 per cent Pb, 1 per cent Ni.....	74	3170	.009	.190	.035	.391
96.5 per cent Pb, 3.5 per cent Ni.....	32	3260	.021	.134	.057	.199

The disadvantages of the nickel-lead alloys are their low strength and difficulty of preparation due to the great difference between the melting points of the components.

Clamer has patented compositions of ferronickel alloys for production of noncorrodible sheets, rods, etc. These contain approximately—

	Per cent
Nickel.....	25-50
Copper.....	5-20
Iron.....	Balance.

(See list of patents.)

An alloy of 30 per cent tantalum and 70 per cent nickel is reported to be resistant to the action of boiling aqua regia (400). Siemens-Halske has patented similar compositions for this purpose.

7. MISCELLANEOUS ALLOYS

Besides its use as a principal alloying element in the well-known alloys just considered, nickel enters into the composition of a great variety of other commercial and experimental alloys in which it acts perhaps principally to increase the hardness without appreciable loss of ductility. However, it is considered to exercise other functions as well in such compositions. In Table 28 are assembled

data on the chemical composition and use of a number of miscellaneous alloys containing nickel in commercial use or mentioned in the literature; this table does not include alloys which have been listed in Tables 20 and 27 under nickel-silver alloys and those for electrical purposes.

Nickel is used to some extent, particularly abroad, as a component of aluminum bronzes to which it appears to impart desirable properties. Parker (240) has pointed out the desirability of studying the possibilities of these alloys for the construction of high-speed superheated steam blading and mentions several compositions which are in commercial use in Great Britain:

Composition	Per cent	Per cent	Per cent
Copper.....	82.07	79.63	79.0
Aluminum.....	2.54	9.77	11.5
Nickel.....	14.64	4.13	5.0
Manganese.....	Nil	.94	Nil
Zinc.....	.68	Nil	Nil
Iron.....	Trace	4.80	4.5
Silicon.....	.04	.14	.....

Bronzes of similar composition containing aluminum and nickel have also been produced commercially under such names as aluminum silver and minargent as substitutes for nickel silver. They have a fine white color and will take a good polish.

Read and Greaves (425, 431) have contributed results of extensive tests of aluminum-nickel bronzes of this type. These alloys were found to forge and roll satisfactorily and to have good mechanical properties, the hardness increasing with the nickel content. Table 51 contains the results of some of their tensile tests on rolled and annealed alloys. Corrosion tests in fresh and sea water carried out by these investigators indicated that the presence of nickel in aluminum bronzes decreases markedly the corrosion of the alloy in sea water; it does not seem to affect the corrosion of the alloy in fresh water in any definite manner. These conclusions are shown in the results of their tests given in Table 53.

The properties of light-aluminum alloys containing nickel have been studied by Read and Greaves (425), Merica, Waltenberg, and Finn (419), and Merica and Karr (420), and it seems to have been demonstrated that nickel in amounts up to 4 per cent added to aluminum will produce an alloy which will roll and work very readily and have quite satisfactory mechanical properties. Thus

an alloy containing 3.9 per cent of nickel in the form of rolled and annealed sheet possessed the following tensile properties:

Tensile strength, pounds per square inch	20 000
Elongation in 2 inches, per cent.	24

However, it does not appear that light alloys containing nickel are as strong, hard, and resistant to corrosion as those which have been hardened with copper, manganese, or zinc in similar amounts and would therefore not give much promise of replacing present commercial wrought light alloys of the copper-aluminum, copper-magnesium-aluminum, or zinc-aluminum type.

Promising results have been obtained, however, with the addition of from 1 to 2 per cent of nickel in light-aluminum casting alloys containing also from 2 to 3 per cent of copper, and there seems to be some possibilities of development in this direction. Thus Merica and Karr have obtained the following tensile test results with a sand-cast alloy containing 3 per cent copper, 0.8 per cent manganese, and 1.5 per cent nickel:

Tensile strength, pounds per square inch	24 000-25 000
Proportional limit, pounds per square inch	6 000- 7 000
Elongation in 2 inches, per cent.	8.5

In this connection it might be noted that nickel is used in the casting alloy, magnalite, and in certain varieties of magnalium produced abroad; these will contain from 1 to 2 per cent of the nickel.

TABLE 50.—Miscellaneous Alloys Containing Nickel

Name of alloy	Chemical composition (per cent)								Remarks
	Ni	Cu	Fe	Zn	Mn	Al	Pb	Sn	
Aphtit.....	20-21	70-75	.....	5.2-2.2	.....	.....	.....	.....	Cd 4.5-1.8
Ajax.....	25-50	5-20	30-70	.....	.....	.....	.....	.....	Bearing metal, gun mountings
Aluminum—nickel	76.4	.....	.....	.....	.....	23.6	.....	20	Ag 10
Aluminum—silver.	20	57	20	.....	.....	3	.....	.....	.....
Aluminum wire(B)	1.3	1	.....	.....	.....	97.7	.....	.....	.....
Argozie.....	14	54	.....	28	.....	.....	2	.....	Castings
Ashberry metal....	1-3	2-3	.....	1-3	.....	.....	.....	78-80	Sb 14-20. Tableware
Aterite.....	12-18	55-60	6-10	13-20	.....	.....	1-2.5	.....	Valves and valve parts
Bario metal.....	90	.....	.....	.....	.....	.....	.....	.....	W 1.22, Si 0.29, Cr 4.25. Heat and acid resist- ing alloy
Bearing metal.....	10.4	.....	.....	.....	.....	.....	.....	83.3	6.3 W. For high speeds
Bismuth brass.....	31	47	.....	21	.....	.....	.1	.....	Bi 0.1
Bismuth bronze....	24	25	.....	.....	.....	.....	.....	.....	Sb 50, Bi 1
Do.....	10	53	.....	20	.....	1	.....	15	Bi 1
Do.....	32.5	45	.....	21.5	.....	.....	.....	16	Bi 1

TABLE 50.—Miscellaneous Alloys Containing Nickel—Continued

Name of alloy	Chemical composition (per cent)								Remarks
	Ni	Cu	Fe	Zn	Mn	Al	Pb	Sn	
Chromax bronze...	15.2	66.7	.....	12.1	.....	3.0	.....	.....	Cr 3.0. Can be rolled. Tensile strength 79 000 lbs./in. ² ; 3 per cent elongation
Cooperite.....	80	.....	.....	.....	.....	.....	.....	.....	W 14, Zr 6. Cutting tools
Cuniloy.....	65	25	.....	.....	35	.....	1	.....	Resistance to corrosion and alkalis
Cufenium.....	22	72	6	.....	.....	.....	.....	.....	Knives, forks, spoons
English nickel (complex).....	2	2	.....	.....	1	.....	.....	87	Bi 0.5, W 1.5, Sb 6
Ilium.....	60.6	6.4	.....	.....	.....	.....	.....	.....	Mo 4.6, Cr 21. Acid resistance; see p. 78
Invar.....	37	.....	63	.....	.....	.....	.....	.....	37 per cent nickel steel; see p. 70
Machine bronze...	25	50-90	.....	.30	.....	.....	0-8	0-30	
Do.....	25	50	.....	.....	.....	.....	.....	25	
Manganin.....	8-10	80	.....	.....	10-12	.....	.....	.....	See p. 77
Minargent.....	39.77	56.82	.....	.....	.....	.57	.....	.....	W 2.84
Do.....	32	46	.....	.....	.....	.....	22	.....	
Mira metal.....	0.24	74.7	.43	.62	.....	.....	16.3	.91	Sb 6.8. For cocks, pipes, etc., to resist acid corrosion
Neogen.....	12	58	.....	27	.....	.5	.....	2	
Nickel-aluminum bronze.....	10	88	.....	.....	.....	2	.....	.....	
Do.....	40	10	.....	.....	.....	30	.....	20	
Nickel bronze.....	30	86	.....	.....	.....	.....	.....	11	
Do.....	20	60	.....	12	.....	.....	.....	8	
Do.....	25	50	.....	.....	.....	.....	.....	25	
Nickeloy.....	1.41	4.15	.....	.....	.....	93.8	.....	.....	Cast gives 20 000 lbs./in. ² tensile strength, 4.5 per cent elongation
Nickel-manganese bronze.....	2.5	53.4	.....	39	1.7	.2	.3	2.6	
Nickel tungsten...	25-50	.....	.....	.....	.....	.....	.....	.....	W 50-75. Alloy for mixing
Nickel zirconium...	86.4	.....	.....	.....	.....	6	.....	.....	Si 6, Zr 1.5, C 0.1. High-speed cutting tools
Plastic bronze.....	1	64	.....	.....	.....	.....	30	5	
Platinite.....	46	.....	54	.....	.....	.....	.....	.....	46 per cent nickel
Platinum substitute	72	.....	.....	.....	.....	23.6	.....	.....	Bi 3.7, Au 0.7
Platnam.....	58.8	32.55	.48	.....	.....	.32	12.72	.....	Used for valve seating
Rosein.....	40	.....	.....	.....	.....	30	.....	20	Ag 10. Used for jewelers' work
Sea-water bronze..	32.5	45	.....	5.5	.....	.....	.....	16	Bi 1. Resistant to sea water
Sheathing bronze..	32.5	45	.....	5.5	.....	.....	.....	16	Bi 1.5
Sidraphte.....	23	5	65	.....	.....	.....	.....	.....	W 4, Sb 3
Speculum.....	4	64	.....	.....	.....	.....	.....	32	For telescopes. Does not always contain nickel
Stanniol.....	.3	1	.1	.....	.....	.....	2.4	96.2	

TABLE 50.—Miscellaneous Alloys Containing Nickel—Continued

Name of alloy	Chemical composition (per cent)								Remarks
	Ni	Cu	Fe	Zn	Mn	Al	Pb	Sn	
Stellite.....	1	.....	2	.....	.....	.....	.....	.....	Co 75, Cr 16.5, Si 3-4, C 2. Pocket and table knives, surgical instruments, machine tools
Stuffing-box alloy..	15.5	61.5	.....	11	.....	.....	10	2	For turbines
Toncas metal.....	28.6	35	7	7	.....	.....	7	7	Sb 7. Ornamental work
Trabuk.....	5.5	.....	.....	.....	.....	.....	.....	87.5	Sb 5, Bi 2. Substitute for nickel silver; re- sistant to vegetable acids
Tungsten brass.....	.....	.....	.....	.....	.....	.....	.....	.....	See wolfram brass
Turbadium bronze	2	48	.....	46	.....	.....	.....	.....	.....
Turbiston bronze..	2	55	.84	41	0.16	1	.....	.....	Resistant to salt water
Typewriter metal..	20	57	.....	20	.....	3	.....	.....	Used for typewriter parts
Unmagnetizable watch wheels.....	18	18	.....	.....	.....	.....	.....	.....	Pt 62.75, Cd 1.25. Used for watch wheels
Warne's metal.....	26	.....	.....	.....	.....	.....	.....	37	Bi 26, Co 11
White gold.....	59	.....	.....	.....	.....	.....	.....	.....	Au 41. Substitute for platinum
Do.....	15	.....	.....	.5	.....	.....	.....	.....	Au 80. Substitute for platinum
White solder.....	10	45	.....	45	.....	.....	.....	.....	Soldering
Wolfram brass.....	14	60	.....	22	.....	.....	.....	.....	W 4
Zanium.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

TABLE 51.—Tensile Properties of Nickel-Aluminum-Copper Alloys (Read and Greaves, 431)

[These values apply to rolled and annealed (900° C) 1 inch diameter rods from 2½-inch ingots]

Chemical composition			Tensile properties			
Cu	Ni	Al	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area
Per cent	Per cent	Per cent	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
89.94	.....	10.06	32 200	57 500	9.0	10.4
87.66	2.46	9.88	40 500	71 500	12.3	13.0
85.11	4.95	9.94	40 400	77 400	16.2	17.4
82.82	7.48	9.70	42 100	87 000	13.1	15.1
94.98	.....	5.02	11 600	49 600	82.5	78.9
93.96	.94	5.10	11 800	51 000	94.6	76.1
92.68	2.38	4.94	12 300	51 300	90.2	71.0
89.84	4.84	5.32	21 100	57 200	70.0	60.2
87.48	7.31	5.21	53 700	87 400	25.6	26.8

Nickel has been substituted for a portion of the tin in government bronze with good results (Burgess and Woodward, 229); these investigators give results of tensile tests of castings. (See Table 52.)

TABLE 52.—Tensile Tests of Government Bronze Castings Containing Nickel

Composition, per cent	Tensile strength	Yield point	Elonga- tion	Reduction of area
	Lbs./in. ²	Lbs./in. ²	Per cent	Per cent
88 Cu, 5 Sn, 5 Ni, 2 Zn.....	40 700	13 100	31.8	28.0
89 Cu, 4 Sn, 4 Ni, 3 Zn.....	39 700	11 500	31.2	31.2

These results may instructively be compared with the American Society for Testing Materials specifications for government bronze of composition 88 Cu, 10 Sn, 2 Zn, as follows: Tensile strength, 30 000 pounds per square inch; elongation in 2 inches, 14 per cent. The proposal has also been made to substitute nickel for a portion of the copper in the same composition (228) by using some cupro-nickel scrap in making the alloy.

TABLE 53.—Corrosion Tests of Rolled and Annealed Nickel-Aluminum-Copper Alloys (Read and Greaves, 431)

Chemical composition			Corrosion loss in weight per month		Chemical composition			Corrosion loss in weight per month	
Cu	Ni	Al	Sea water	Fresh water	Cu	Ni	Al	Sea water	Fresh water
Per cent	Per cent	Per cent	Lbs./ft. ²	Lbs./ft. ²	Per cent	Per cent	Per cent	Lbs./ft. ²	Lbs./ft. ²
89.94	.....	10.06	0.00091	0.00009	94.98	.....	5.02	0.00031	0.00006
89.55	0.97	9.48	.00022	.00006	94.04	0.92	5.04	.00031	.00008
85.15	4.94	9.91	.00012	.00011	90.09	4.90	5.01	.00012	.00007
80.13	9.98	9.81	.00009	.00009	85.08	10.07	4.85	.00002	.00012

Nickel is a powerful decolorizing agent for metals such as copper and gold. Several jewelers' white alloys are produced to-day as substitutes for platinum under the name of white gold; they contain from 20 to 50 per cent of nickel with the balance of gold.

An alloy of 90 per cent of nickel and 10 per cent of tin is used to some extent for valve seats and rings.

Nickel in small amounts has been found to exert a beneficial effect on copper-lead bearing bronzes in preventing the segregation of the lead. Thus a much-used railway bearing bronze for heavy bearings contains—

		Per cent			Per cent
Copper.....	64		Lead.....	30	
Tin.....	5		Nickel.....	1	

An alloy of nickel and zirconium called Cooperite (see Table 28) after its discoverer has been patented for machine tools and appears to have shown some very interesting test results in comparison with ordinary high-speed steel.

PART C. APPENDIXES

1. DEFINITIONS OF PHYSICAL TERMS

Absorption Index.—When monochromatic light traverses a distance equal to its own wave length λ , in a material, is the ratio of the amplitude of the emergent light J'_λ to that of the entering light J°_λ

$$\frac{J'_\lambda}{J^\circ_\lambda} = e^{-2\pi\kappa}$$

when κ is the absorption index.

(A variety of usage prevails regarding the definition of this term. This definition is used in the Smithsonian physical tables.)

Density.—The density of a substance is the mass per unit volume. It is usually expressed in terms of grams per cubic centimeter.

Electrical Conductivity and Resistivity (χ , ρ).—There are two methods of expressing electrical resistivity in common use, each being defined quantitatively in terms of the resistance of a unit specimen. The volume resistivity is ρ in the equation

$$R = \frac{\rho l}{s}$$

in which R =resistance, l =length, and s =cross section. The volume resistivity thus defined may be expressed in various units, such as microhm-cm (microhm per centimeter cube), ohms per foot of a uniform wire 1 mil in diameter, etc. The commonly used units, in abbreviated terminology, are: microhm-cm, microhm-inch, ohm (meter, mm), ohm (meter, mm²), ohm (mil, foot).

The other kind of resistivity is mass resistivity, and is defined as δ in the equation

$$R = \frac{\delta l^2}{m}$$

in which m =mass of the wire. The usual units of mass resistivity are: ohm (meter, gram), and ohm (mile, pound).

PER CENT CONDUCTIVITY.—The term "conductivity" means the reciprocal of resistivity, but it is used very little in wire calculations. In connection with copper, however, extensive use is made of the per cent conductivity, which is calculated in practice by dividing the resistivity of the International Annealed Copper Standard at 20° C by the resistivity of the sample at 20° C.

TEMPERATURE COEFFICIENT OF RESISTANCE.—The temperature coefficient of electrical resistance is the fractional change of resistance per degree change of temperature. Its value varies with the temperature, and hence the temperature from which the resistance change is measured must always be stated or understood. For a temperature t_1 , the temperature coefficient t_1 is defined, for a metal like copper, by

$$R_t = R_{t_1} [1 + \alpha_{t_1} (t - t_1)],$$

in which R_{t_1} =resistance at the temperature t_1 and R_t =resistance at any other temperature t . The temperature coefficient that is usually used at 20°, for example, is

$$\alpha_{20} = \frac{R_t - R_{20}}{R_{20}(t - 20)}$$

BOILING POINT.—The boiling point of a liquid is the temperature at which it boils under atmospheric pressure, or better the temperature at which its vapor pressure is equal to the external pressure.

BRINELL TEST.—An indentation is made, by pressure, on a polished surface of the material, using a hardened steel ball. There are several ways of expressing the hardness:

The commonest definition of the Brinell hardness is the pressure in kilograms per unit area (square millimeters) of the spherical indentation. (Hardness numeral = H. N.)

$$\text{H. N.} = \frac{\text{Pressure}}{\text{area of spherical indentation}} = \frac{P}{t\pi D}$$

where

$$t = D/2 - \sqrt{D^2/4 - d^2/4}$$

P = pressure used.

t = depth of indentation.

D = diameter of sphere.

d = diameter of indentation.

ELECTROLYTIC SOLUTION POTENTIAL (E).—At the junction of a metal and any conducting liquid there is developed a solution potential, which is a measure of the free-energy change of the chemical reaction which is possible at the surface of the metal and liquid. In particular if the chemical reaction consists in the solution of the metal, forming ions, the emf is given by the formula

$$E = \frac{RT}{nF} \log_e \frac{P}{p}$$

R = the gas constant.

T = absolute temperature.

n = valence of metal.

F = 96 500 coulombs, the Faraday constant.

P = solution pressure of metal.

p = osmotic pressure of metal ion formed in solution.

In any electrolytic cell the sum or difference of two such potentials is measured, one of which may be a standard electrode; for example, the hydrogen or the calomel electrode. The emf of an electrolytic cell of the following type: Metal — solution — normal hydrogen electrode is often called the single emf (e_h) for the metal in the solution; that is, arbitrarily assuming the emf of the normal hydrogen electrode to be zero.

EMISSIVITY (E OR E_λ).—The coefficient of emissivity E for any material represents the ratio $\frac{J'_\lambda}{J_\lambda}$ of the intensity, J'_λ , of radiation of some particular wave length or color, λ , emitted by the material at an absolute temperature T to that, J_λ , emitted by a black body radiator at the same temperature.

The coefficient of total emissivity E for any material represents that ratio $\frac{J_1}{J}$ of the intensity of radiation of all wave lengths, J_1 , emitted by the material at an absolute temperature, T , to that, J , emitted by a black body radiator at the same temperature.

This coefficient is always less than 1, and for metals is equal to 1 minus the reflection coefficient for normal incidence (Kirchhoff's law).

For any optical pyrometer using monochromatic light a value of the observed or "black body" temperature of any substance (not inclosed) is reduced to the true temperature by the following formula:

$$\frac{1}{T} - \frac{1}{T_0} = \frac{\lambda \log_{10} E_\lambda}{6232}$$

T = true absolute temperature.

T_0 = observed absolute temperature.

λ = wave length in microhm (0.001 mm).

E_λ = relative emissivity of substance for wave length.

ERICHSEN TEST.—This test is carried out to determine the ductility of sheets. An indentation is made in the sheet with a die with hemispherical end. The greatest depth of indentation which can be made without incipient cracking of the sheet, measured in inches or millimeters, is known as the Erichsen value for the sheet.

HEAT OF FUSION.—The heat of fusion of a substance is the quantity of heat absorbed in the transformation of unit mass (1 g) of the solid substance to the liquid state at the same temperature.

MAGNETIC PROPERTIES.—The usual magnetic characteristics of a substance are given either by the permeability, μ , or the susceptibility, κ . Permeability is the ratio of the magnetic induction (B : in gaussess per square centimeter) to the magnetizing force (H : in gaussess per square centimeter). This is indicated by the relation

$$\kappa = \frac{B}{H}$$

Susceptibility is given, in corresponding units, by

$$\kappa = \frac{\mu - 1}{4\pi}$$

For all materials except iron and a few other ferromagnetic metals μ is very nearly unity and κ is only a few millionths. When κ is positive in sign the substance is paramagnetic, when negative diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicated by κ_v . A quantity called mass susceptibility is also used, and is equal to the volume susceptibility divided by the density of the material; it is represented by κ_m .

MELTING POINT.—The melting or fusing point of a substance is the temperature at which it fuses (under atmospheric pressure), or more accurately the temperature at which the solid and the liquid metal are in equilibrium with each other.

PELTIER EFFECT (π).—When at the junction of two metals current flows from one to the other, heat is in general absorbed or liberated (see "thermoelectromotive force" below); the coefficient, the amount of heat liberated when a unit quantity of electricity flows across the junction, is known as π (measured either in calories per coulomb or in volts), the Peltier effect.

REFRACTIVE INDEX.—The ratio of the velocity of light in vacuum to that in any material is called the refractive index (n) of that material. (This physical quantity ceases to have a meaning at or near an absorption band in the material.)

SCLEROSCOPE TEST (SHORE).—A hardened hammer falls from a constant height onto a polished surface of the material, and the distance of rebound is measured on a scale 10 inches long, divided into 140 equal parts. The scleroscope hardness is expressed as the distance of rebound on this arbitrary scale, the value 100 representing the hardness on this scale of hardened steel.

SPECIFIC HEAT (σ).—The true specific heat of a substance is $\frac{du}{dt}$ when u is the total internal heat or energy of unit mass of the substance. The mean specific heat is defined as $\frac{q}{t_1 - t_2}$ per unit mass when q is the quantity of heat absorbed during a temperature change from t_2 to t_1 . It is generally considered as the quantity of heat (calories) required to raise the temperature of unit mass (grams) by unity (degrees centigrade), either at constant volume or at constant pressure. Unless otherwise noted the specific heat of solids refers to that at constant (atmospheric) pressure. The true specific heat (constant pressure) of metals may usually be expressed sufficiently by an equation of the type

$$\sigma = A + Bt + Ct^2 + \dots$$

TENSILE TEST.—The quantities determined in the tension test are the following:

The *ultimate tensile strength* is the maximum load per unit area of original cross section borne by the material.

The *yield point* (American Society for Testing Material) is the load per unit of original cross section at which a marked increase in the deformation of the specimen occurs without increase of load.

The *elastic limit* (American Society for Testing Materials) is the greatest load per unit of original cross section which does not produce a permanent set.

The *proportional limit* (American Society for Testing Materials) is the load per unit of original cross section at which the deformations cease to be directly proportional to the loads.

The *percentage elongation* is the ratio of the increase of length at rupture between arbitrary points on the specimens to this original length.

The *percentage reduction of area* is the ratio of the decrease of cross section at the "neck" or most reduced section at rupture to the original section.

THERMAL CONDUCTIVITY (λ).—The coefficient of thermal conductivity (λ) expresses the quantity of heat (small calories) which flows in unit time (seconds) across a unit cube (centimeter) of the material whose opposite faces differ in temperature by unity (1°C.). Its *temperature coefficient* is expressed as

$$\alpha_{t_0} = \frac{\lambda_t - \lambda_{t_0}}{\lambda_{t_0}(t - t_0)}.$$

THERMAL EXPANSION.—If l_t is any linear dimension of a solid at any temperature $\frac{dl}{dt}$ is the linear coefficient of thermal expansivity of that solid in the direction of l . It is not in general proportional to the temperature except approximately over small temperature intervals, but may be expressed in the following manner:

$$\frac{dl}{dt} = a + bt + ct^2 \dots$$

For small temperature intervals a mean coefficient (α) is often determined; that is,

$$\alpha_{t_0} = \frac{l_t - l_{t_0}}{l_{t_0}(t - t_0)}$$

THERMOELECTROMOTIVE FORCE (E).—In an electric circuit composed of two dissimilar conductors, the two junctions being at different temperatures, there exists in general an electromotive force, called the thermoelectromotive force, between the two metals, the value of which is a function both of the temperature and the difference of temperature between the two junctions. It is shown thermodynamically that this emf is related to the Thomson and Peltier effects in the following manner:

$$\left. \begin{aligned} \pi &= \frac{T}{J} \frac{dE}{dt} \\ \sigma_1 - \sigma_2 &= -\frac{T}{J} \frac{d^2E}{dt^2} \end{aligned} \right\} \text{and expressed in calories per coulomb when } J = \frac{4.18 \text{ dynes} \times 10^8}{\text{calories}}$$

when E is the thermal emf, T the absolute temperature, $\frac{dE}{dt}$ the thermoelectric power (see below), and $\sigma_1 - \sigma_2$ the difference in the Thomson effect of two materials. The form of the function $E = E(T)$ is not known. In general the equation $\frac{dE}{dt} = A + BT$ satisfactorily fits the experimental data over a limited range of temperature of a few hundred degrees.

It has been shown that the Thomson effect for lead is practically zero. This metal has served as a comparison metal in studying the thermoelectric forces of others.

THERMOELECTRIC POWER.—If E is the thermoelectromotive force of any two dissimilar metals, $\frac{dE}{dt}$ = the thermoelectric power; it is at any temperature therefore approximately the thermal emf of a couple of which the temperatures of the two junctions differ by 1°C.

THE THOMSON EFFECT.—When a current flows in a conductor from a point at one temperature to one at another, heat is in general liberated, or absorbed, and an emf

or counter emf is produced. The coefficient of the Thomson effect is the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature, t , to one at a temperature, $t+dt$, and is equal to σdt calories per coulomb where σ is the so-called Thomson specific heat of electricity. It is called positive for any material when heat is generated in that material as a current flows from a region of higher to one of lower temperature.

2. LIST OF UNITED STATES PATENTS ON NICKEL ALLOYS EXCLUSIVE OF NICKEL STEEL, 1900-1920

Patent No.	Date	Patentee	Device or process patented
648428	1900	J. Patrick.....	Use of magnesium with cast nickel.
646118	1900	G. H. Clamer.....	Use of 1 per cent nickel in copper-lead.
655392	1900	J. G. Henderson.....	Alloys to prevent segregation.
702996	1902	W. Pruszkowski.....	Alloys of iron, manganese, nickel, cobalt, and aluminum.
709268	1902	D. P. James.....	Copper-tin-nickel-silver-aluminum alloy.
811239	1906	A. Monel.....	Manufacture of Monel metal.
824103	1906	W. B. Driver.....	Electrical-resistance alloy.
824618	1906	C. H. Birmingham....	Silver-nickel-bismuth-gold alloy.
827717	1906	T. A. Edison.....	Composite metals.
834099	1906	.....	Nickel-lead.
839444	1906	G. F. Allen.....	Nickel-copper-lead.
846851	1907	A. Hobson.....	Copper-zinc-nickel-manganese alloy.
854462	1907	G. E. Buttenshaw....	Copper-zinc-nickel-lead alloy.
859608	1907	A. L. Marsh.....	Electrical-resistance alloy.
864139	1907	W. Rubel.....	Copper-iron-nickel-aluminum alloy.
864140	1907	W. Rubel.....	Zinc-aluminum-silicon-copper.
873346	1907	.....	Nickel-chromium.
901428	1908	J. T. H. Dempster....	Electrical-resistance alloy.
926980	1909	Dempster.....	Add chromium and manganese to nickel.
937285	1909	{E. B. Craft..... J. W. Harris.....}	Alloy with nickel for electrical contacts.
938422	1909	G. Hartmann.....	Aluminum solder containing nickel.
939938	1909	C. F. Ackermann.....	Copper-nickel-zinc
943066	1909	William B. Driver....	Electrical-resistance alloy.
959156	1910	{J. Naulty..... J. Scanlin.....}	Chromium-copper-nickel-zinc alloy
961217	1910	W. B. Driver.....	Electrical-resistance alloy.
963123	1910	J. T. H. Dempster....	Do.
965871	1910	G. H. Clamer.....	Manufacture of iron-nickel-copper alloy.
974419	1910	{J. Naulty..... J. Scanlin.....}	Alloys of copper with chromium and nickel alloys.
981542 993042	1911	W. B. Driver.....	Electrical-resistance alloy.
1003806	1911	A. J. Rossi.....	Titanium-nickel alloy.
1012391	1911	A. L. Marsh.....	Utensil holder (chromium-nickel).
1016549	1912	G. H. Clamer.....	Iron-nickel-copper alloy.
1020513	1912	A. J. Rossi.....	Purifying nickel.
1044761	1912	J. F. Duke.....	Iron-copper-nickel alloy.
1050342	1913	G. H. Clamer.....	Do.
1057755	1913	A. L. Marsh.....	Nickel-silicon resistance alloys.
1069113	1913	J. Coup.....	Copper-nickel-zinc-aluminum-phosphorus alloy.
1070007	1913	.....	Add aluminum and zinc to nickel.
1076455	1913	W. Rubel.....	Iron-nickel-manganese-aluminum alloy.
1086314	1914	G. H. Clamer.....	Manufacture of nickel-iron-copper alloy.
1093557	1914	E. D. Gleason.....	Iron-nickel-copper-aluminum boiler tubes.
1103482	1914	{C. Canzler..... R. Samesreuther.....}	Alloy for welding copper and nickel.

2. LIST OF UNITED STATES PATENTS ON NICKEL ALLOYS EXCLUSIVE OF NICKEL STEEL, 1900-1920—Continued

Patent No.	Date	Patentee	Device or process patented
1106206	1914	C. E. Guillaume.....	Nickel-iron alloy for springs, peculiar elastic properties.
1106207			
1110303	1914	H. Kreusler.....	Manufacture of alloys of tungsten and nickel.
1114055	1914	E. Smith.....	Copper-nickel-zinc-tin alloy.
1115239	1914	S. W. Parr.....	Illum.
1127624	1914	G. C. Holder.....	Nickel-lead-copper for packing rings.
1147398	1915	R. H. Henemier.....	Nickel-aluminum-copper for tire valves.
1162226	1915	C. R. Denton.....	Copper-nickel-zinc alloys.
1163813	1915	P. J. A. Douglass.....	Hardening nickel-copper alloys.
1164840	1916	P. G. Miller.....	Uniting nickel-alloy pipe to vitreous ware.
1168074	1916	M. A. Hunter.....	Electrical-resistance alloy.
1175172	1916	W. E. Oakley.....	Nickel-iron-copper valve alloy (Monel).
1175724	1916	W. B. Driver.....	Chromium resistance alloy.
1180996	1916	H. W. Gaskill.....	Copper-nickel-zinc-manganese alloy.
1190652	1916	J. C. Henderson.....	Chromium-nickel alloy for high temperatures.
1203180	1916	T. B. Brix.....	Nickel alloy.
1203555			
1211943	1917	M. A. Hunter.....	Electrical resistance alloy.
1217578	1917	W. B. Driver.....	Do.
1221769	1917	H. S. Cooper.....	Zirconium-nickel-iron for tools.
1223001	1917	H. K. Sandell.....	Copper-antimony-lead-nickel bearings. Nickel-carbon for spark points.
1223002			
1229037	1917	H. S. Cooper.....	Nickel-silver-palladium, electrical contacts.
1240055	1917	R. M. Keeney..... L. F. Vogt.....	Nickel-uranium alloy.
1244742	1917	C. L. Jones.....	
1252038	1918	H. K. Sandell.....	Gold-tungsten-nickel for dental work.
1257272	1918	G. M. Laird.....	Electrical-resistance alloy.
1263831	1918	M. R. Walford.....	Heat-resistance nickel-iron alloy.
1268495	1918	H. K. Sandell.....	Nickel-tungsten electrical contacts.
1274395	1918	W. B. Driver.....	Alloy, spark plugs.
1277989	1918	F. Milliken.....	Copper-nickel-zinc alloy.
1274250	1918	W. B. Driver.....	Electrical-resistance alloy.
1273877	1918	P. R. Kuehnrich.....	Nickel-iron-copper-aluminum tools.
1278304	1918	H. S. Cooper.....	Nickel-aluminum-zirconium-silicon for tools.
1277046			
1279448	1918	H. K. Sandell.....	Nickel-copper-iron alloy.
1291408	1919	L. W. Chubb.....	Nickel-iron for high magnetic permeability.
1305551	1918	H. C. Kirk.....	Aluminum-nickel-copper alloy, light.
1310363	1918	F. Millikin.....	Copper-nickel-zinc-iron.
1314417	1918	do.....	Zinc-nickel-iron-manganese.
1340451	1918	T. Koch.....	Gold-nickel-manganese jewelry alloy.
1341540	1920	J. P. Copland.....	Alloy of iron with chromium, nickel, tungsten, and manganese for cast furnace linings.
1346188	1920	F. A. Fahrenwald.....	Nickel-chromium-iron alloys for gun barrels.
1346189			
1346190			
1346191			
1349918	1920	M. N. Salvati.....	Alloys of nickel and zinc.
1350166	1920	F. Milliken.....	Copper-nickel-iron-zinc alloy for electrical resistance.
1350359	1920	H. S. Cooper.....	Zirconium-nickel alloy for cutting tools.
1351673	1920	F. Milliken.....	Copper-nickel-lead alloy, mine water valves.
1351811	1920	A. Tedesco.....	Nickel-copper-tungsten alloy, noncorrosive, high electrical resistivity.

3. TYPICAL SPECIFICATIONS FOR NICKEL ALLOYS

46M1aMAR. 1,
1916SUPERSEDING
46M1
June 20, 1913

NAVY DEPARTMENT SPECIFICATIONS

MONEL METAL, CAST, OR COMPOSITION Mo-c

(Standard Stock Catalog designation: Monel metal (Composition Mo-c), cast)

GENERAL SPECIFICATIONS

1. General specifications for inspection of material, issued by the Navy Department, in effect at date of opening of bids, shall form part of these specifications.

CHEMICAL PROPERTIES

2. The chemical requirements are as follows:

Copper, minimum	Nickel, minimum	Iron, maximum	Aluminum, maximum	Manganese, maximum	Carbon and silicon combined, maximum
Per cent 23.0	Per cent 60.0	Per cent 3.5	Per cent 0.5	Per cent 3.5	Per cent 0.8

PHYSICAL PROPERTIES

3. The physical properties of the metal shall conform to the requirements of the table given below:

Minimum tensile strength (pounds per square inch)	Minimum yield point (pounds per square inch)	Minimum of elonga- tion in 2 inches
65 000	32 500	Per cent 25

WORKMANSHIP

4. The castings must be made in accordance with the drawing and specifications—sound, clean, free from blowholes, porous places, cracks, or any other defects which will materially affect their strength or appearance or which indicate an inferior quality of metal.

TEST LOTS

5. Castings weighing less than 250 pounds finished may be tested by lot or heat, a lot not to exceed 250 pounds and a heat not to exceed 500 pounds of finished castings. Each lot or heat will be represented by one test specimen when attached to a casting or when a casting is sacrificed to obtain a test specimen.

TEST COUPONS

6. If the castings are too small for the attachment of coupons, the test pieces may be cast separately, from the same metal, under as nearly as possible the same conditions as the casting. Where test pieces are cast separately from the castings, two pieces will be required, one to be poured before and one after the castings. Coupons shall not be detached from castings until they are stamped by the inspector. If the test pieces are cast separately from the casting, they must be cast in the same flask with the casting and must be removed from it in the presence of the inspector and stamped by him at the time they are taken out of the molds.

FRACTURE

7. The color of the fracture section of test pieces and the grain of the metal must be uniform throughout.

PURPOSES FOR WHICH USED

8. The material is suitable for the following purposes: Valve fittings, plumbing fittings, boat fittings, propellers, propeller hubs, blades, engine framing, pump liners, valve seats, shaft nuts and caps, and composition castings requiring great strength.

SPECIFICATIONS, WHERE OBTAINABLE

NOTE.—Copies of the above specifications can be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES

S. E., 169686-687-4-S, Jan. 12, 1916.
C. & R., Z46M1a-M, Jan. 21, 1916.
Ord., 29752/167 (Br)-O, Jan. 21, 1916.
S. & A., 380-938.

46M7bMAY 1,
1917**SUPERSEDING**
46M7a
Feb. 1, 1916**NAVY DEPARTMENT SPECIFICATIONS****ROLLED MONEL METAL (COMPOSITION Mo-r), BARS,
PLATES, RODS, SHEETS, ETC.****GENERAL SPECIFICATIONS**

1. General Specifications for Inspection of Material, issued by the Navy Department, in effect at date of opening of bids, shall form part of these specifications.

SCRAP

2. Scrap shall not be used in the manufacture, except such as may accumulate in the manufacturers' plants from material of the same composition.

CHEMICAL REQUIREMENTS

3. The chemical properties shall be as follows:

Copper, minimum	Nickel, minimum	Iron, maximum	Aluminum, maximum	Manganese, maximum	Carbon and silicon, combined maximum
Per cent 23.0	Per cent 60.0	Per cent 3.5	Per cent 0.5	Per cent 3.5	Per cent 0.8

PHYSICAL REQUIREMENTS

4. The physical properties of the metal shall conform to the requirements of the tables given below:

RODS AND BARS

	Minimum yield point per square inch	Minimum ultimate tensile strength per square inch	Minimum elongation in 2 inches
Rounds and squares:	Pounds	Pounds	Per cent
Up to and including 1 inch.....	40 000	80 000	25
1 1/16 inches to and including 1 11/16 inches.....	50 000	85 000	28
1 3/4 inches to and including 2 7/16 inches.....	45 000	80 000	30
2 1/2 inches to and including 3 1/2 inches.....	37 000	77 000	32
Over 3 1/2 inches.....	40 000	75 000	32
Rectangles.....	40 000	75 000	32
Hexagons.....	40 000	80 000	32

SHEETS AND PLATES

Tensile strength, minimum pounds per square inch	Yield point, mini- mum pounds per square inch	Elonga- tion, mini- mum in 2 inches
65 000	30 000	Per cent 15

NOTE.—No material less than 1/4 inch in thickness or diameter need be tested physically.

ADDITIONAL TESTS

5. All bars shall stand—

(a) Being hammered hot to a fine point.

(b) Being bent cold through an angle of 120° and to a radius equal to the diameter or thickness of the test bar.

SURFACE INSPECTION

6. Material shall be free from all injurious defects, clean, straight, smooth, of uniform color, quality, and size, and within the gauge and weight tolerances.

TRIMMING

7. (a) *Rods and bars.*—Rods and bars will be received in stock lengths unless it is specifically stated that exact lengths are required. Stock lengths will be as follows:

1 to 4 inches, 8 to 20 feet

Over 4 inches, 6 to 20 feet

(b) *Plates and sheets.*—Plates and sheets will be cut to the required dimensions and will be ordered in as narrow widths as can be used.

TOLERANCES

8. No excess weight will be paid for, and no single piece that weighs more than 8 per cent above the calculated weight will be accepted. The base or unit weight for such calculations shall be taken as 558 pounds per cubic foot, or .323 pound per cubic inch.

UNDERWEIGHT TOLERANCES

	Tolerance
Widths of sheets or plates:	Per cent
Up to 48 inches.....	5
48 to 60 inches.....	7
Over 60 inches.....	8

NOTE.—Material shall not vary throughout its length or width more than the given tolerance.

FRACTURE

9. The color of the fracture section of test pieces and the grain of the material shall be uniform throughout.

PURPOSES FOR WHICH USED

10. The material is suitable for parts requiring strength or incorrodibility, such as propeller-blade bolts, air-pump and condenser bolts, and pump rods.

NOTE FOR SUPPLY OFFICERS

The material covered by these specifications will be called for as follows:

Monel-metal, rolled, bar and rod.

Monel-metal, rolled, plate and sheet.

SPECIFICATIONS, WHERE OBTAINABLE

NOTE.—Copies of the above specifications can be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES:

- S. E., 220933 4 687-S, Apr. 4, 1917.
C. & R., Z46M7b, Apr. 9, 1917.
Ord., 29752/344 (B2)-O, Apr. 11, 1917.
S. & A., 380-938.

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